ELSEVIER

Marine Geology 195 (2003) 5–30

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

Giant carbonate mud mounds in the southern Rockall Trough

Neil H. Kenyon[a,*], Andrey M. Akhmetzhanov[a], Andrew J. Wheeler[b], Tjeerd C.E. van Weering[c], Henk de Haas[c], Michael K. Ivanov[d]

[a] *Southampton Oceanography Centre, Empress Dock, European Way, Southampton SO14ZH, UK*
[b] *Coastal Resources Center, University College Cork, Cork, Ireland*
[c] *Netherlands Institute for Sea Research (NIOZ), P.O. Box 59, 1790 AB Den Burg, Texel, The Netherlands*
[d] *UNESCO-MSU Centre for Marine Geosciences, Faculty of Geology, Moscow State University, Vorobjevy Gory, Moscow 119899, Russia*

Received 21 May 2001; accepted 5 November 2002

Abstract

Seismic profiles, sidescan sonar data, bottom photography and sampling proved for the first time that there are giant carbonate mounds (bioherms) in the Rockall Trough. The Pelagia Mounds, on the northern Porcupine Bank, are relatively isolated whereas most of the Logachev Mounds, on the southeast Rockall Bank, form a field of closely spaced, contiguous mounds. They are all found on the upper slope at depths between about 500 and 1200 m and as a result of this study about 500 have been mapped. They have a variety of shapes and the larger ones are very steep-sided, up to 350 m high and 2 km wide at the base. Sediment samples show that the mounds consist of pale coloured muds, mainly aragonite, usually with live and/or dead cold-water corals at the seafloor and with buried dead corals. Coral thickets appear to be detected as a brush-like signature on high resolution profiles and as a speckled pattern on high resolution sidescan sonar records. Shelly sands are found on the seabed between the mounds. Currents in the mound areas are strong enough to transport sands along slope as medium-sized sand waves and to prevent pelagic deposition, thus providing surfaces for initial coral settlement by the winnowing of fines to leave glacial dropstones and exposed rocks. These observations show that the poleward-directed upper slope current of the eastern North Atlantic extends further south than hitherto known and that there is a southwesterly directed current on Rockall Bank. There are waves on the Logachev Mounds, with a wavelength of about 20–30 m, that are thought to be moulded in carbonate muds by across-slope directed internal tidal currents and/or cascading currents. Mounds develop above erosional surfaces seen on seismic data. The huge amount of carbonate mud seems to be produced by the rapid growth and breakdown of cold-water corals living in a very favourable environment. Intermediate nepheloid layers formed upstream by the strong currents may provide the food source for the deep water suspension feeders. Conditions for giant mound growth require an ideal balance between current speed and sedimentation rate, among other factors. No evidence for the suggested link to methane seepage has been found so far.

Keywords: Northeast Atlantic; mud mounds; deep water corals; bottom currents; sediment transport; internal waves

* Corresponding author. Tel.: +44-1703-596570; Fax: +44-1703-596554.
E-mail address: n.kenyon@soc.soton.ac.uk (N.H. Kenyon).

1. Introduction

Comprehensive investigations were conducted

0025-3227/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0025-3227(02)00680-1

on the Rockall Trough margins during the 7th TTR Cruise in 1997 onboard R/V *Professor Logachev* (Fig. 1). The aim was to study in detail some mounded seabed features which had been observed on industry and academic seismic data. These features had not been sampled and so their origin was in question, although they occurred at similar depths (approximately 500–1000 m) to the possible carbonate mounds described from the Porcupine Basin (Hovland et al., 1994).

2. Methods

The dataset discussed here was obtained using a number of methods. High resolution single-channel seismic profiles were collected using a 1.8-l sleeve gun, shooting at 10-s intervals. The received signals were amplified and filtered. The onboard processing included additional filtering and prestack deconvolution. Seismic profiling was carried out simultaneously with OKEAN 10-kHz long-range sidescan sonar recording. In selected areas, where higher resolution of seabed features was required, an OREtech deep-towed sidescan sonar, operating at 30- and 100-kHz frequencies and equipped with a 5-kHz subbottom profiler, and also an underwater TV system, were employed. Seabed sampling sites were chosen after analysis of the sonographs and samples were collected using a large diameter gravity corer, box corer, kasten corer and a large capacity PREUSSAG TV-controlled grab.

Some preliminary data from high resolution sidescan sonar (400 kHz) and closely spaced echo sounder lines, obtained as part of the EC ECOMOUND programme, have also been incorporated in this paper.

3. Results

3.1. The Northern Porcupine Bank margin (Pelagia Mounds)

Mounds were observed on a seismic line (PSAT-13) along the northern Porcupine Bank at a water depth of about 800 m (Fig. 2). They appear on the record (Fig. 3) as several build-ups above a relatively flat seafloor. The largest mound is up to 200 m high and has a base length of about 1500 m. The larger mounds have steep slopes, except where there is sediment banking up against the southwestern side of the mounds. Several seismic units are identified on the line (Fig. 3). Mounds are confined to, and built up on the top of, the uppermost unit, which has a flat surface truncating the underlying beds. Often the internal reflectors within the unit show downlap, which, together with continuity of the reflectors and the erosion at the base, is a typical seismic signature for sedimentary drifts and indicates the presence of a depositional environment influenced by bottom currents. Below the hyperbolic mound profiles the signal is chaotic and indistinct, and appears to be greatly attenuated. Below the largest mound there is a 'pull-up' of underlying strata, probably due to an increase of sound velocity, suggesting that the deposits within the mound are more consolidated. The other mounds do not show such a pull-up, although signal attenuation is also seen. The absence of the pull-up effect for these mounds can be explained by the seismic line side-swiping the mounds rather than going directly over them.

A deep-towed sidescan sonar line was run along the seismic line in 30-kHz mode (medium resolution) to map the location of the mounds and to resolve their morphology. Mounds vary in plan view from near-circular to elongate, with the long axis being up to 2.5 times the short axis. The mounds are smaller at the northeastern end of the line but have very strong acoustic backscatter (Fig. 4). A high resolution (400 kHz) sidescan sonar survey showed that some of these very high backscattering small patches may be rock outcrops, as the survey resolved what seem to be bedding and fault patterns (Fig. 5). Some small mounds are built up on these possible rock patches (Fig. 5). At the southwestern end of the line, medium resolution sidescan sonar mapped more than 30 mounds with a variety of sizes, up to 1.5 km in length, up to 700 m in width and up to 200 m high (Fig. 6). They are distinctly linear and oriented SSW/NNE. The mounds are deduced from the shadow of their crestlines to be

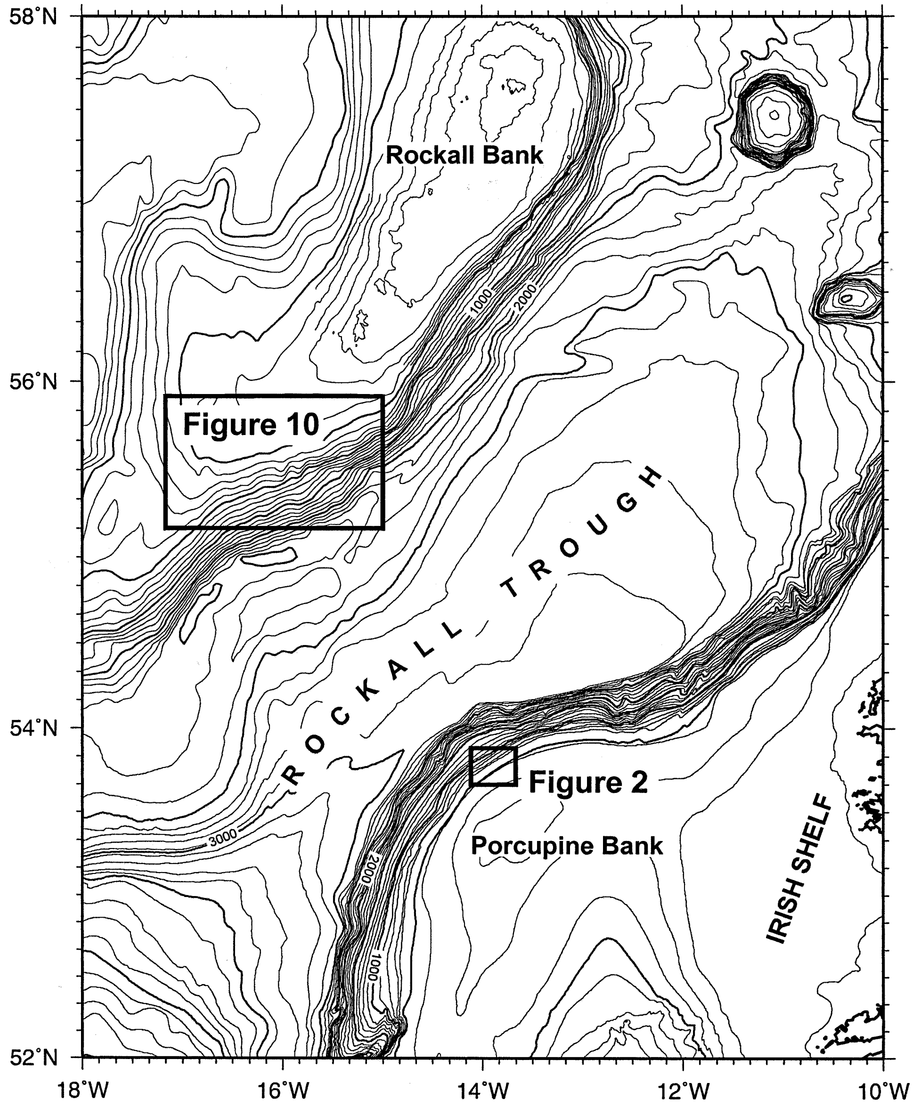


Fig. 1. General map of the Rockall Trough and Porcupine margin showing study areas. Bathymetry from GEBCO-97. Contour interval 100 m.

multi-peaked. This complex morphology is confirmed by close-spaced echosounding (some results of which are shown in Fig. 7) carried out during a R/V *Pelagia* cruise within the framework of the EC ECOMOUND project (De Haas et al., 2000). Smaller mounds, up to 30 m high, are more conical than the larger mounds. Most mounds have rings of high backscatter at their base (Fig. 6), most prominently on their northeastern side. The profiles show that these are deeps or 'moats' partially surrounding the mounds. The seafloor around the larger mounds is higher by 20–30 m on their southwestern side.

Between some mounds there is a low backscatter signature, which extends as northeasterly trending tails for hundreds of metres (Fig. 6). These are interpreted as mobile sand sheets and sand shadows.

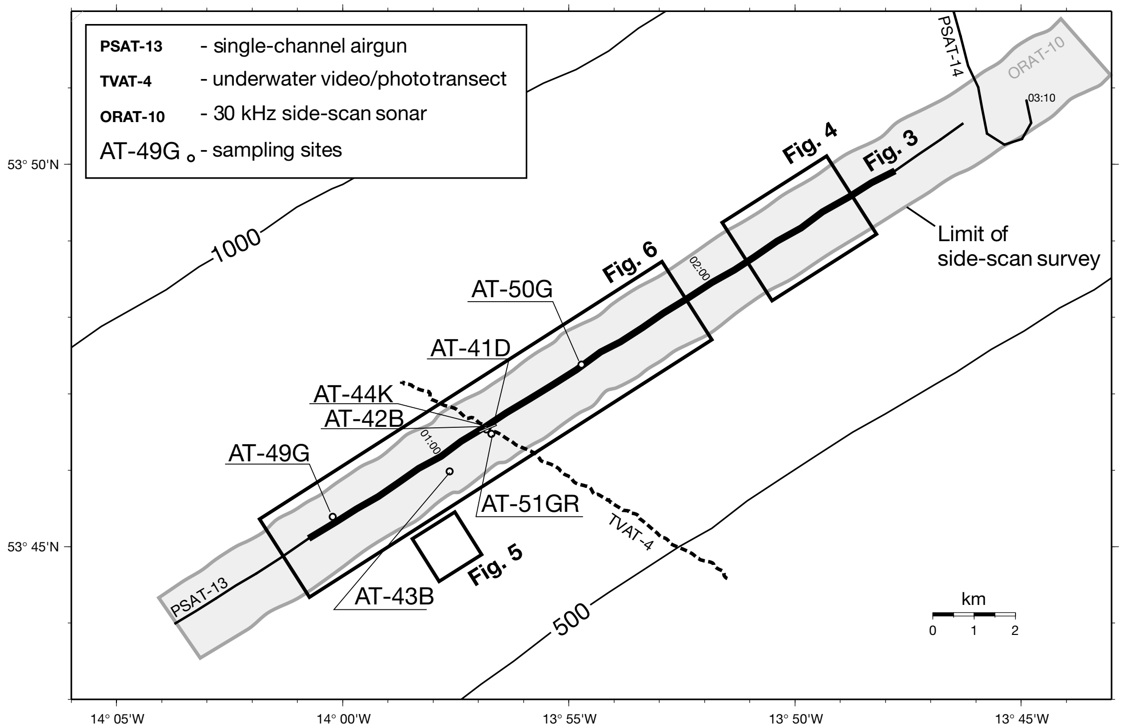


Fig. 2. Location map of data and figures in the northern Porcupine Bank study area.

Six bottom samples were retrieved from the Pelagia Mounds and one from the intermound area. Although most of the cores collected from the mounds were short they do have small amounts of living corals, foraminiferal ooze, shells and dead coral fragments. One core (AT-49G) recovered a 135-cm-long sedimentary sequence (Fig. 6), consisting mainly of two interlayered lithologies. One lithology is predominantly broken corals with a mixture of grey foraminiferal ooze/marl and the other has a slight predominance of grey foraminiferal ooze/marl over coral debris. The marl consists of up to 80% carbonate. The top of the largest mound known in the area was sampled with the PREUSSAG TV-controlled grab which retrieved more than 1 ton of sediment, consisting of a grey marl containing lithic and shell fragments and coral debris. The apparently undisturbed surface consisted mainly of shell debris and a 1–2-cm layer of patchy coral debris (*Lophelia pertusa* and *Madrepora oculata*), one living colony of *M. oculata* (approximately 20 cm in height), one living colony of *L. pertusa* (approximately 20 cm in height), a cidaroid, a hydrozoan, and several bivalves. A box core (AT-43B), taken from a flat area between mounds (Fig. 6), revealed a sequence of coarsening-upward medium to coarse, poorly sorted sand with an olive grey muddy silt layer at the bottom containing two horizons of well-preserved brachiopod shells. The presence of a sequence of coarse sand suggests active hydrodynamic seabed conditions, which supports the sidescan sonar observations. Core AT-50, obtained from one of the high backscattering patches, had almost no recovery apart from a small amount of sandy material, suggesting the presence of a hard substrate with a thin cover of mobile sand.

An underwater TV line was run across the largest mound (Fig. 8a). The video record showed corals mostly inhabiting the very top of the mound (Fig. 9) while the slopes were covered with fine-grained carbonate-rich muds, as deduced from their pale brown/grey colour. The specific

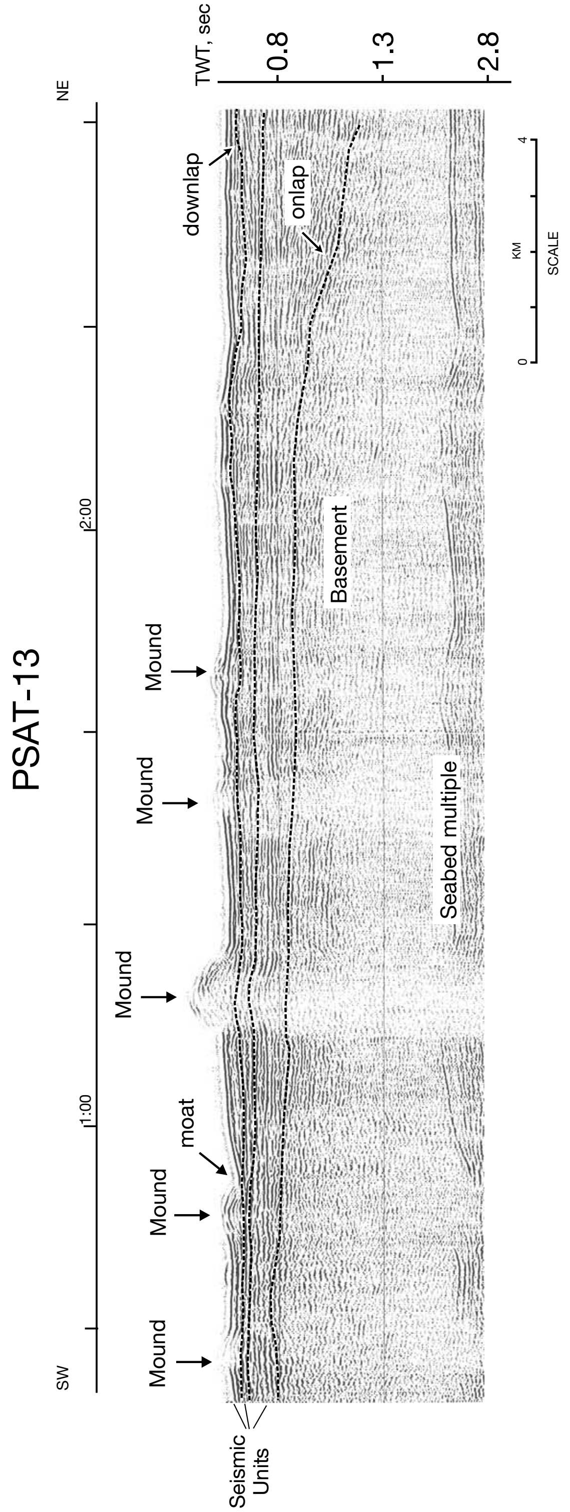


Fig. 3. Seismic line PSAT-13 showing some of the Pelagia Mounds along the northern Porcupine Bank margin. Contourite drifts have built up on the southwest (upstream) side of the mounds.

'brush-like' acoustic character of the 5-kHz subbottom profiler record at the top of the mound (Fig. 8b) is thought to be due to the presence of coral thickets. Such an acoustic signature appears to be a common feature of most of the mounds studied in this area. The 5-kHz profile also shows lens-like acoustically transparent units covering the slopes of the mounds. The observed thickness of these units varies from 2 to 8 m and they are interpreted as coral rubble layers formed by the death of coral colonies. The recognition of such layers indicates that a carbonate mud mound may be built up from the stacking of lens-shaped bodies of dead coral and its breakdown products. At the base of the mound there are very coarse materials, gravel-sized or larger, that are thought to be due to winnowing out of the finer sediments.

3.2. Southwestern Rockall Trough margin (Logachev Mounds)

Mounded features on the southwestern Rockall Trough margin were first drawn to our attention from unpublished proprietary seismic data and had also been recognised on single-channel airgun lines shot by NIOZ in 1987 and 1997 (van Weering et al., in press). Five NIOZ seismic lines were recorded across the margin from the shelf break area down to the basin floor. In 1997 a set of lines running parallel to the margin was acquired during the TTR-7 cruise on the mid to upper slope (papers in Kenyon et al., 1998) (Fig. 10). Seismic profiling was carried out simultaneously with a 10-kHz OKEAN long-range sidescan sonar. The OKEAN image (Fig. 11) shows a gently sloping seafloor with a low acoustic backscatter down to a depth of about 500–600 m. In the northeastern part of the area there are several linear to sinuous features, up to 7 km long and about 150 m wide, which appear to be furrows with ridges on either side. The morphology suggests that these features are iceberg ploughmarks, as first mapped on

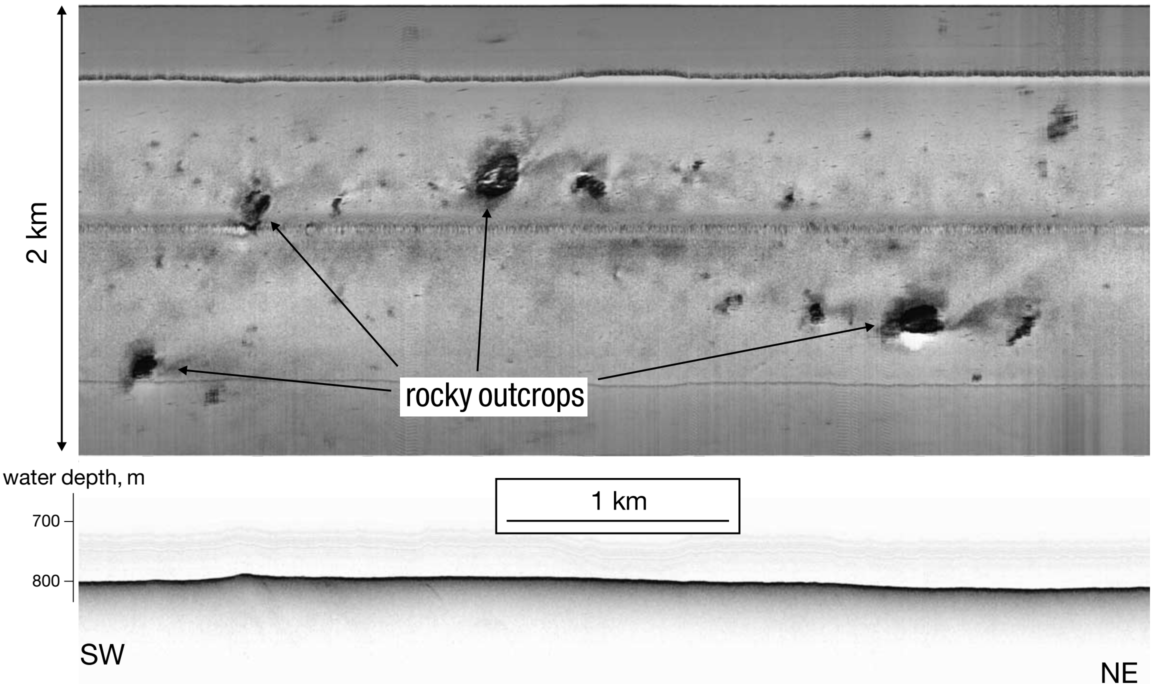


Fig. 4. 30-kHz sonograph, with corresponding 5-kHz subbottom profiler record, showing high backscattering patches (dark tones) interpreted as rocky outcrops, possibly colonised by cold-water corals and small carbonate mud mounds.

Rockall Bank by Belderson et al. (1973). They show a preferred orientation parallel to the slope and are in slightly deeper water depths than is usual for ploughmarks in this part of the North Atlantic. Below 500–600 m water depth the OKEAN mosaic shows a zone with an unusual ('wiggly') acoustic pattern that corresponds to a characteristic mounded relief. The pattern has relatively high backscatter values. In profile it is undulating but interrupted by some near-flat areas of low backscatter. The mounded zone is roughly parallel to the slope and is mainly found at depths of between 600 and 800 m. According to the OKEAN imagery, it extends along the margin for a distance of more than 120 km, with an average width of about 5 km and a maximum width of up to 20 km (Fig. 12). At about 15°30′W a tongue of the mounded topography extends down to 1100 m water depth. The upper part of the zone (500–600 m) is characterised by a slightly different backscatter pattern compared with the lower part (600–1100 m). The lower part of the zone has large clusters of mounds up to 1.5 km across.

Seismic lines across the margin show an acoustically well-stratified sedimentary succession, 60–130 m thick, overlying a highly reflective basement with an irregular and possibly faulted upper surface (van Weering et al., in press). Where seismic lines cross the zone of complex topography, there are mounded features, up to 130 m high, with chaotic internal structure. The tops have multiple hyperbolic reflectors, suggesting a very irregular upper surface. Where the zone is narrow, the mounds appear as massive bodies incorporated into an acoustically well-stratified uppermost package that is underlain by an unconformity, which also forms the base of the mounds. To the northeast, where the width of the mound field reaches up to 20 km, the mounds form the upper surface of an acoustically semi-transparent package blanketing the upper slope. The base of the package is marked by a distinct unconformity (Fig. 13). The upslope pinchout is at the slope

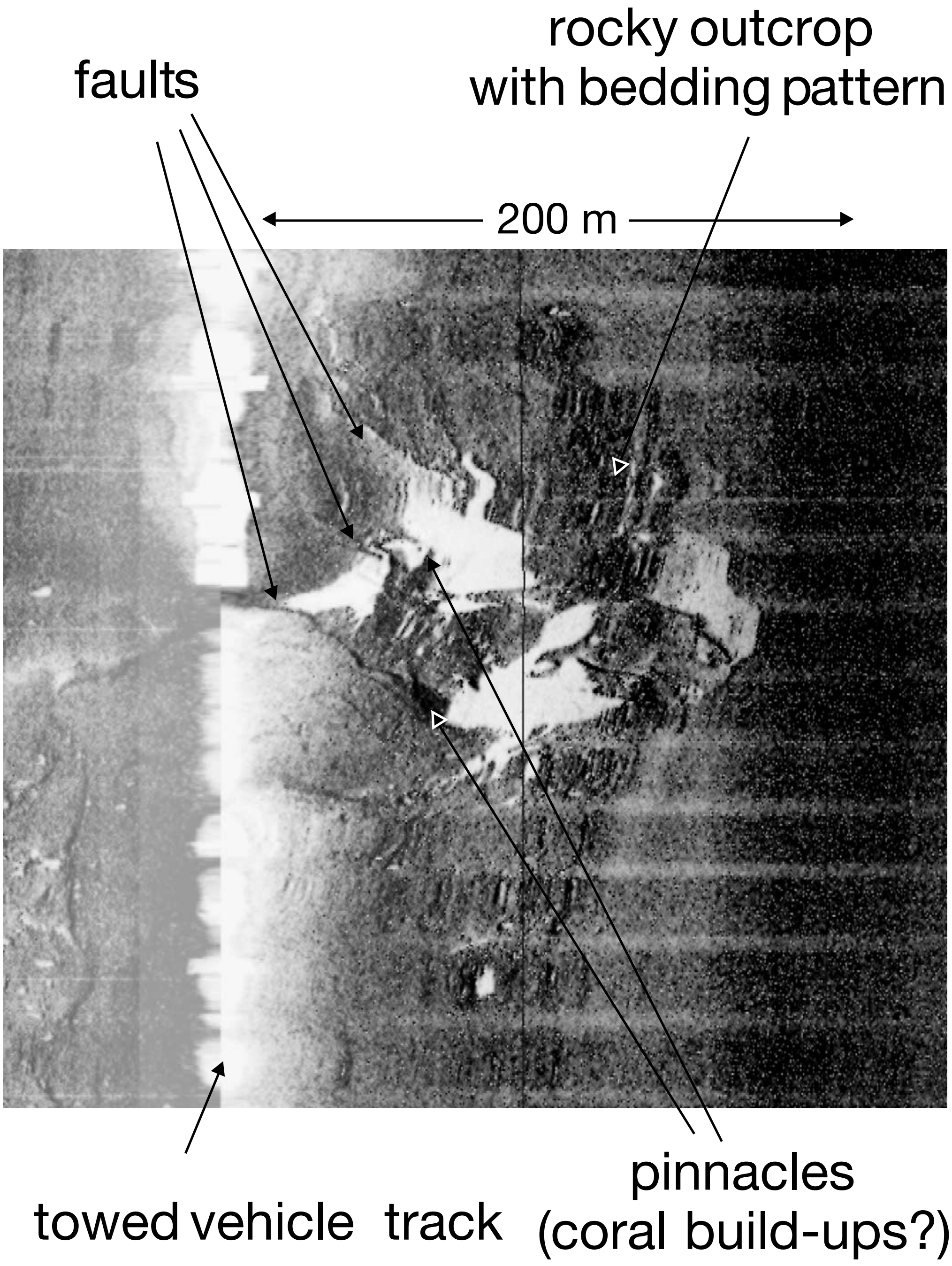
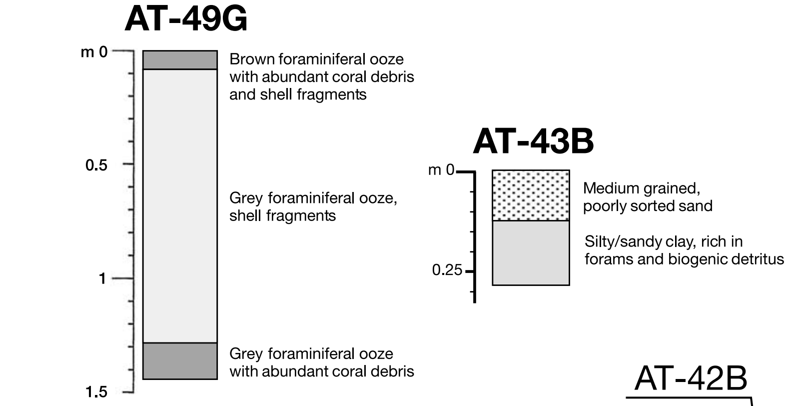


Fig. 5. Fragment of 400-kHz sonograph resolving detail of possible rock outcrop, similar to those observed with lower resolution in Fig. 4. Several pinnacles are detected from their shadows (white) and are interpreted as carbonate build-ups.



CORE	GEAR	RECOVERY, CM	SEDIMENTARY SUMMARY
AT-41D	Dredge	several corals and fauna trapped in the tangles	Corals and allochthonous fauna
AT-42B	Box corer	a few corals and foramineferal ooze	Living corals, foraminiferal ooze, shells and coral fragments
AT-43B	Box corer	27 cm	Coarsening up sequence of sand and muddy silt; layers rich in shells
AT-44K	Kasten corer	10 cm	Mixture of foramiferal ooze, living corals and associated fauna
AT-49G	Gravity corer	135 cm	Corals in the upper part overlying foraminiferal ooze that becomes more consistent towards the bottom and contains decayed corals
AT-50G	Gravity corer	2 cm	Small amount of fine grained foraminiferal sand with clasts of foraminiferal ooze, one clast covered by bryozoans
AT-51Gr	PREUSSAG grab	1 tonne	Foraminiferal ooze, corals, drop stones, lithic fragments, shells

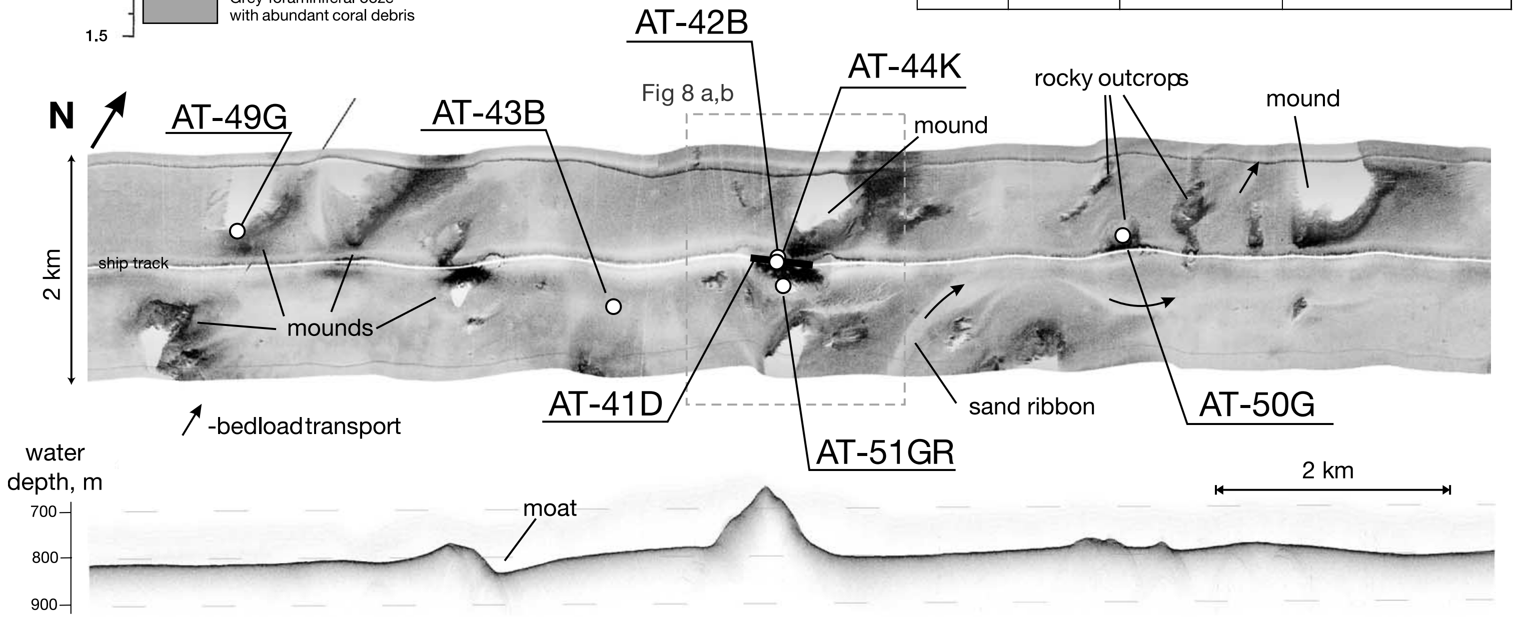


Fig. 6. Fragment of 30-kHz sonograph (ORAT-10) and 5-kHz subbottom profiler with several large carbonate mounds. Location of bottom sampling stations and results of groundtruthing are shown. Dark tones on the sonograph indicate strong acoustic return, shadows are white.

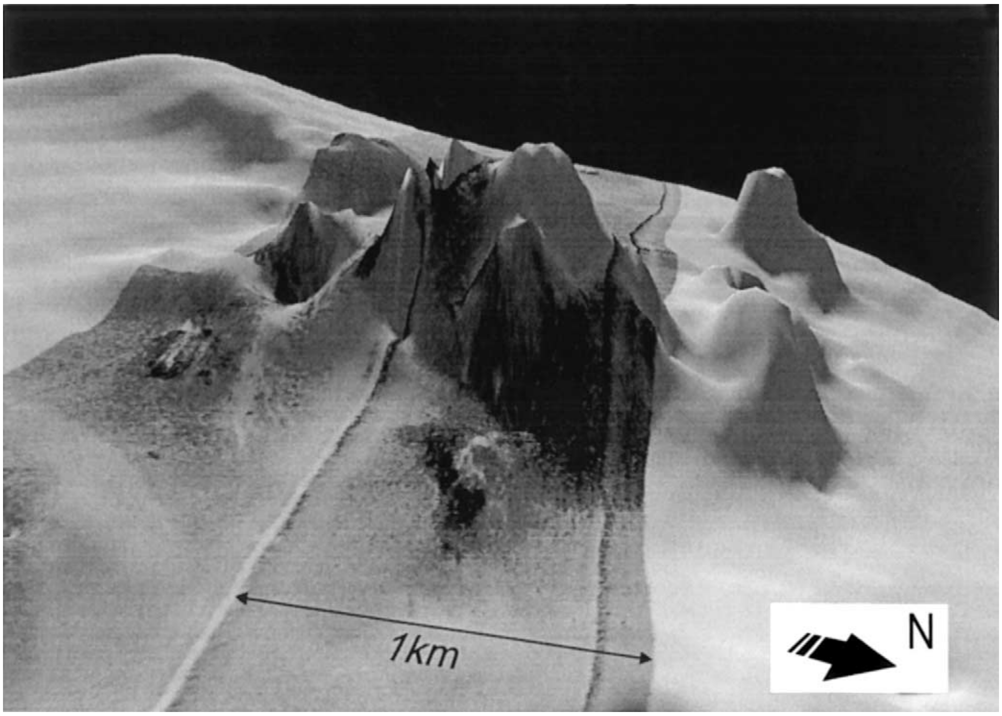
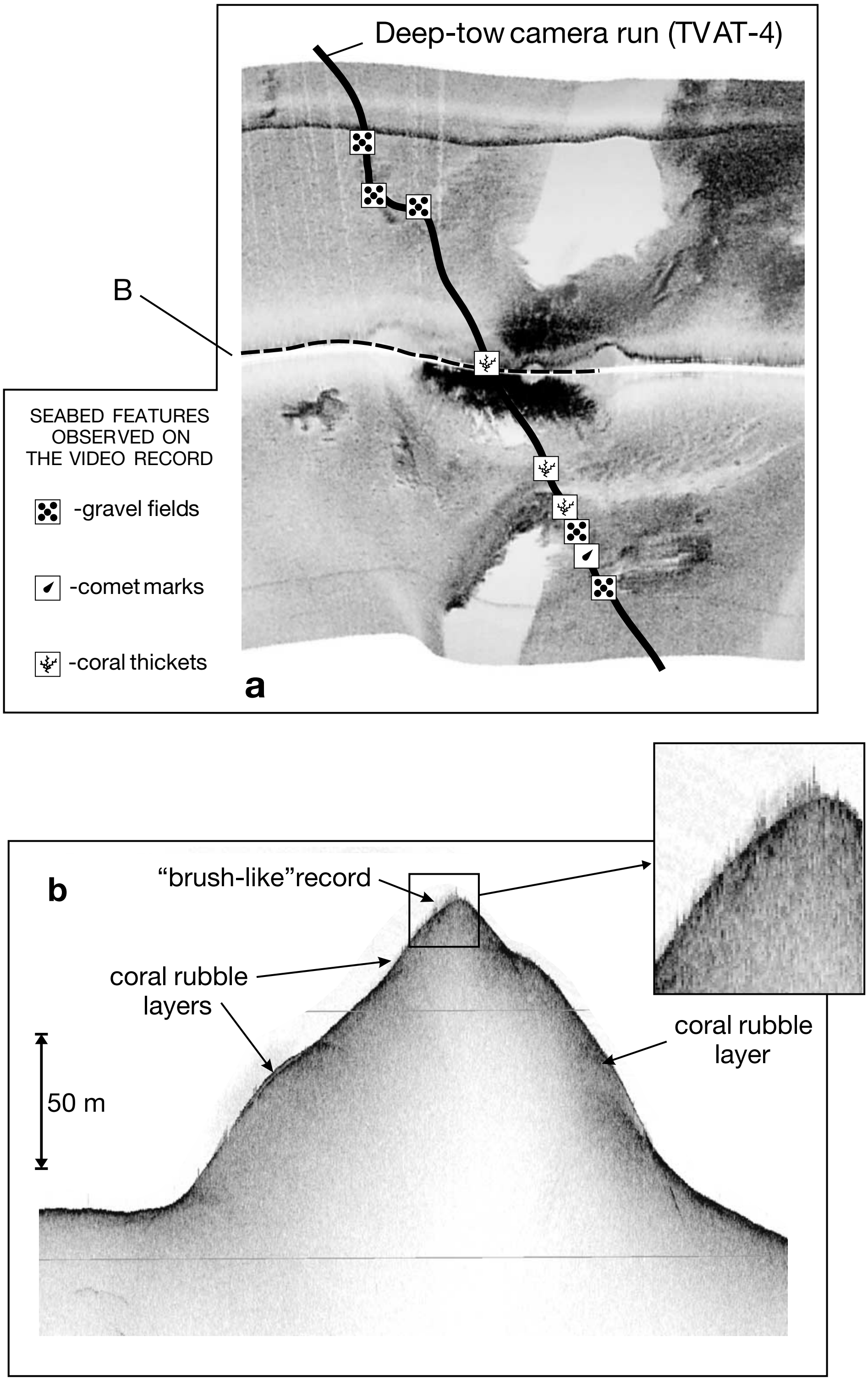


Fig. 7. Perspective view of a portion of 30-kHz sonograph draped over a digital terrain model of a large carbonate mound on the northern Porcupine Bank margin. The image shows the complex, multi-peaked morphology of the mound. Vertical exaggeration is 1:10. Bathymetry is from closely spaced echo sounder lines taken by NIOZ (De Haas et al., 2000).

break, at a depth of about 500 m, while basinward the package pinches out at 1200 m. The highest mounds are found within the larger separate clusters. To the southwest the mounds decrease in height to 50–60 m, although they are still very densely packed. In the southwesternmost part of the survey area, where the seafloor flattens and is characterised by uniform backscatter, the sonar maps only a few individual elongate mounds. At least one of them seems to develop on a basement high protruding through the sedimentary sequence (Fig. 14).

A medium resolution, 30 kHz, sidescan sonar line (ORAT-13) was run parallel to the contours to image a portion of the mound field. A large number of closely spaced mounds are present, some of them conical and others ridge-like. They have a wavelength of about 200–400 m and are typically less than 100 m high (Fig. 15). The mounds are not penetrated by the deep-towed profiler. All of the mounds are ornamented by a regular wave pattern, wavelength between 20 and 30 m, which is aligned roughly along the regional contours (Fig. 16). This pattern is formed in the carbonate muds that are shown by coring to make up most of the mound material. There are some flat-floored intermound areas that are aligned in various directions, including downslope and alongslope. These have a very sandy seafloor, characteristically seen as very low backscatter on the sidescan sonar. The sand is being transported to the south or southwest as determined by the asymmetry of sand waves and comet marks.

A higher resolution (100 kHz) sidescan sonar line was run downslope across a number of provinces identified on the long-range sonar survey (ORAT-14 on Fig. 10). On the upper part of the line the deep-towed fish was unstable, resulting in regular distortions on the sonographs, but it showed a zone of very low acoustic backscatter, presumably due to a sand cover as it is ornamented by regular small waves. This wavy bed-


Deep-tow camera run (TVAT-4)
B
SEABED FEATURES OBSERVED ON THE VIDEO RECORD
-gravel fields
-comet marks
-coral thickets
a
b
"brush-like"record
coral rubble layers
coral rubble layer
50 m

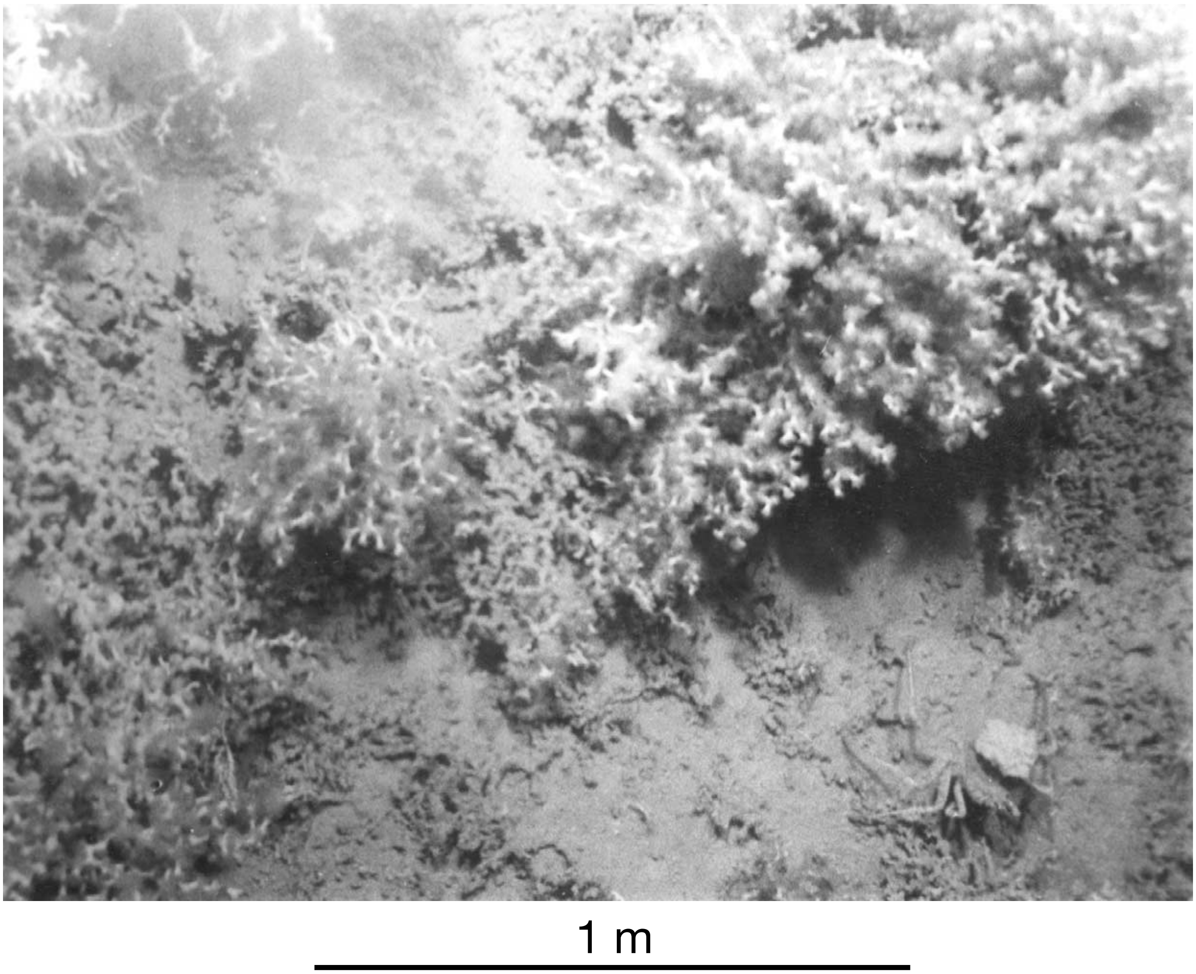


Fig. 9. Still photo taken along the line TVAT-4 and showing thickets of cold-water corals on the top of a mound.

form pattern is interrupted by a number of high-backscattering elongate scours that are thought to be formed by enhanced scouring downstream of boulders. There are also many shallow furrows with ridges on either side, interpreted as iceberg plough marks. In the upper part of the mound field there are many high-backscattering, gentle-sided, small hills and ridges (10–20 m high) with a speckled pattern of very high backscatter (Fig. 17). This latter feature may be due either to boulders, winnowed out from softer and lower backscattering sediments, or to isolated coral colonies, but they are most likely coral colonies attached to stones or boulders. On the lower part of the mound field the mounds are up to 100 m high, with multiple tops, and separated by flat-floored troughs. Downslope from the field of mounds, where the depth is 900 m, there is a 350-m-high

Fig. 8. (a) Track of underwater video line (TVAT-4), located on sidescan sonar record, showing a cold-water coral colony on top of a mound. (b) A 5-kHz subbottom profile along line B shows the brush-like signature that associated with coral thickets and also penetration through possible rubble layers.

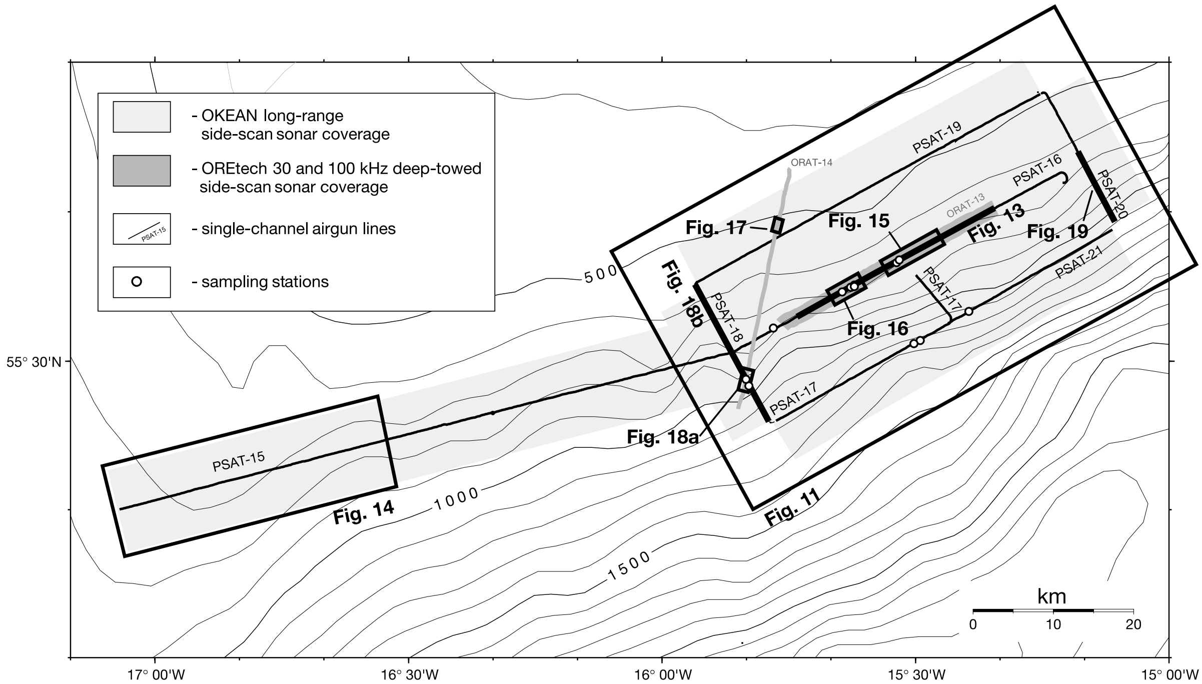


Fig. 10. Location map of the southwestern Rockall Trough margin study area.

isolated mound. It also has an ornamentation of fairly straight-crested waves along its flanks (Fig. 18a), moulded in a relatively high-backscattering material that is presumed to be carbonate mud. A seismic profile shows that the large mound has grown on a pre-existing acoustic basement high (Fig. 18b).

Samples recovered from the tops of the mounds are mainly composed of grey foraminiferal ooze, broken branches of corals, including living species, coral and shell debris (Table 1). Corals are normally found with an associated fauna in which there is a high diversity of sponges and polychaetes. Forty eight species were provisionally identified (Kenyon et al., 1998), with suspension feeders being recognised as the dominant feeding type.

All of the long cores retrieved from different mounds recovered a similar sedimentary sequence consisting mainly of alternating layers of grey foraminiferal ooze/marl containing greater or lesser amounts of coral debris (*Lophelia pertusa* and *Madrepora oculata*) (Figs. 16 and 18; Table 1). Cores taken from the intermound areas recovered small amounts of poorly sorted, medium-grained sand, rich in shell and coral fragments. It is similar to the carbonate sand described by Scoffin et al. (1980) from higher up on Rockall Bank. Three cores, taken at about 1200-m water depth from the mid-slope area below the mound field, also contained only a small amount of fine- to medium-grained sand.

4. Discussion

4.1. Comparison of mounds on either side of the Rockall Trough

This study proves that carbonate mud mounds are common features on both sides of the southern Rockall Trough. They are typically found in a water depth range of 550–1200 m. Bathymetric profiles of individual mounds show a similar morphology, with relatively steep flanks on the larger mounds, probably because the sticky muds and dead corals that they are composed of form a structure that is not prone to failure (Fig. 18).

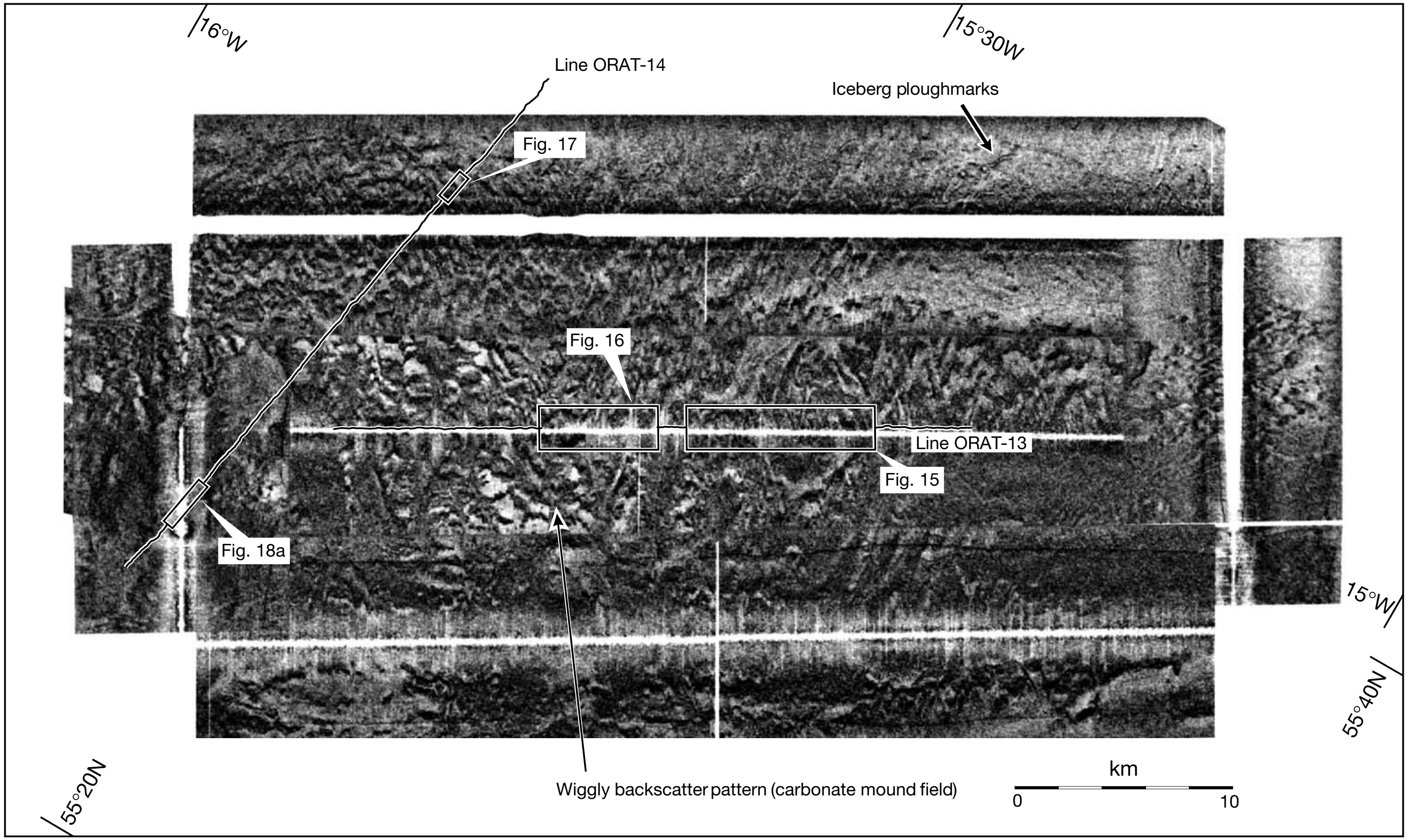


Fig. 11. 10-kHz OKEAN mosaic showing the pattern of closely spaced carbonate mounds in the Logachev Mound area (Rockall Bank). Location of medium resolution (30 kHz) (Figs. 15 and 16) and high resolution (100 kHz) (Figs. 17 and 18a) sidescan sonar lines is also shown.

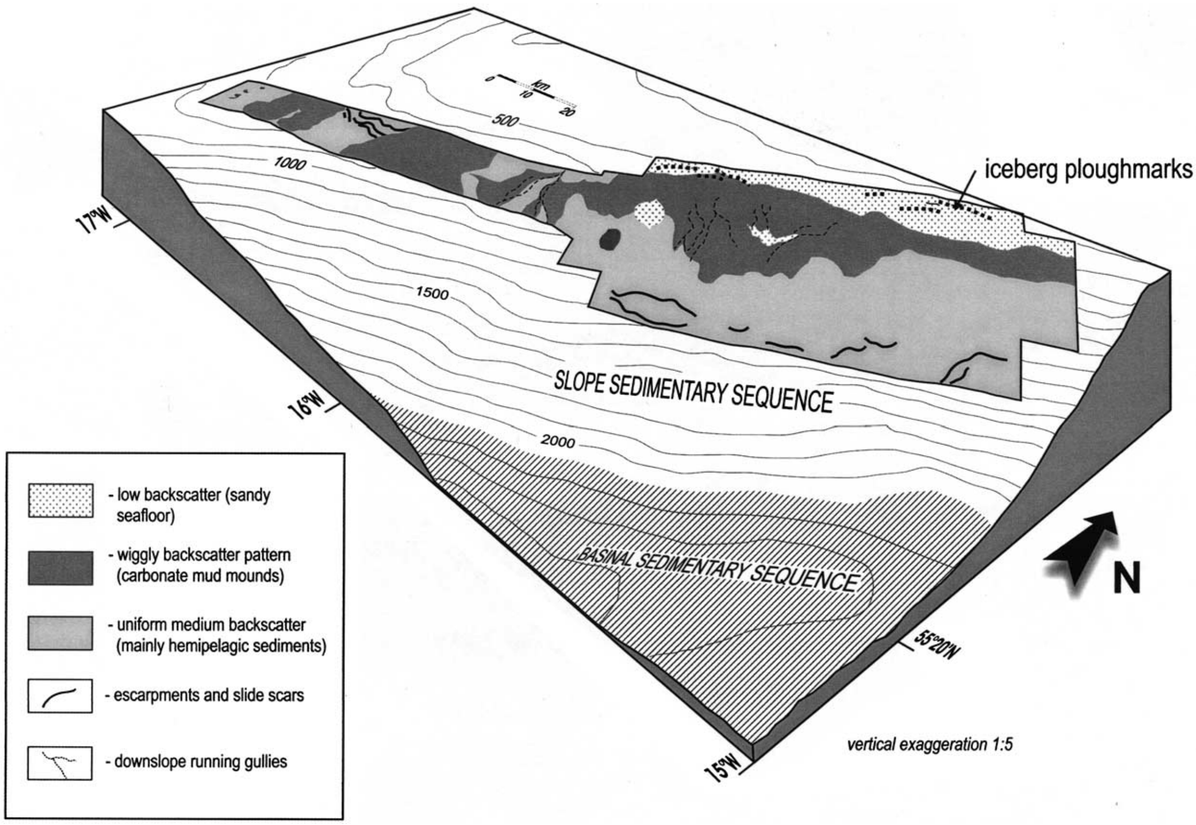


Fig. 12. Block diagram of a portion of the southwestern Rockall Bank margin showing the field of carbonate mud mounds and other surface sedimentary environments, based mainly on interpretation of the long-range sidescan sonar data.

The mounds seem to have their upward growth limited to a depth of about 650 m, as the summits of most of the large mounds are found at this particular depth. The Pelagia Mounds on the eastern Rockall Trough form a belt of isolated build-ups extending parallel to the slope at depths of 600–800 m. The individual mounds are similar to large mounds described from the seafloor of the Porcupine Basin (Hovland et al., 1994; Kenyon et al., 1998). Their shape is clearly affected by bottom currents as most of the larger mounds show a preferred orientation parallel to flow direction as determined from bedforms (Kenyon et al., 1998).

The Logachev Mounds on the upper–middle slope of the western Rockall Trough margin have a much denser distribution and form a large field stretching along the margin. Only a few individual mounds are seen on long-range sonographs. Some of the mound clusters are found outside of the main mound field and seismic records clearly show that they are associated with outcrops of the basement and have reached a height of up to about 350 m above the surrounding seafloor.

Cores taken from the mounds recovered a succession of interbedded layers of foraminiferal ooze/marl and layers of coral debris. This is similar to the succession recovered from the Porcupine Basin mounds (Hovland et al., 1994; Kenyon et al., 1998) from which a study of coccolith assemblages suggests that the presence of ooze layers with abundant coral debris is the result of an increase of growth of coral colonies during interglacial periods, whereas ooze layers with small amounts of debris are attributed to glacial periods, at which time the development of the colony had ceased (Saoutkine, 1998). Live corals

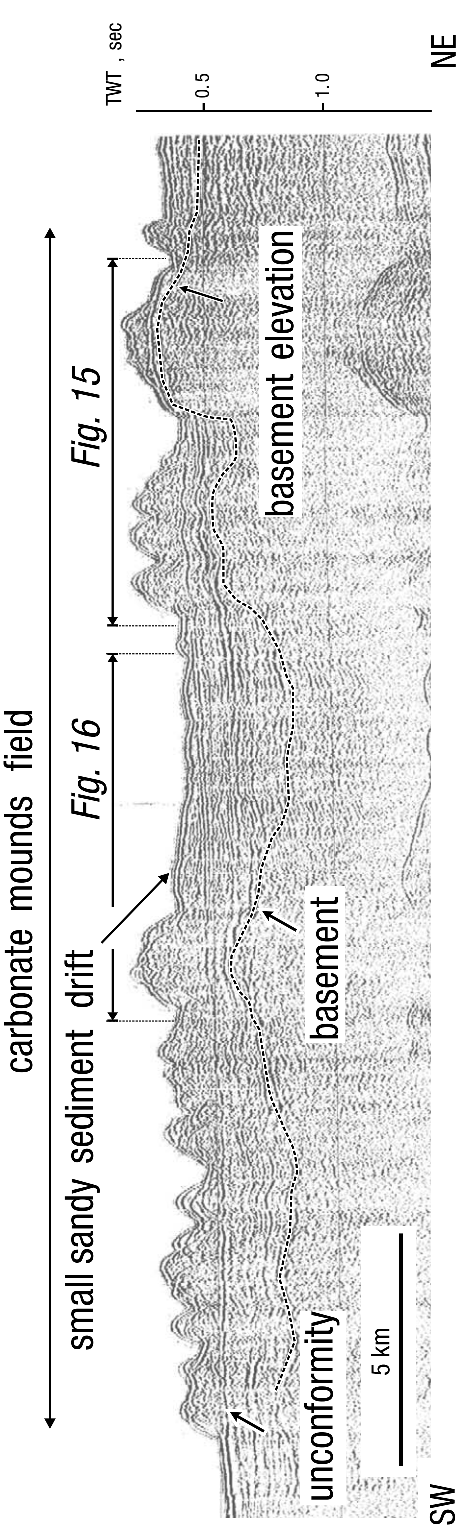


Fig. 13. Section of single-channel airgun profile (PSAT-16) across part of the Logachev Mound field. Note that the mounds are up to about 100 m high and have built on a distinct unconformity and occasionally on a basement high of presumed igneous rocks.

and sequences of coral rubble have been recovered from these mound tops and it is believed that they represent the most recent stage of mound development with actively growing communities of cold-water corals.

These groups of mounds in the northeast Atlantic closely resemble deep water lithoherms from the Florida–Hatteras slope (Paull et al., 2000). However, they seem to lack cementation, unlike the lithoherms from the warmer waters of the sub-tropical western Atlantic, and so are called here mud mounds.

4.2. Environmental conditions

Sidescan sonar surveys show abundant evidence that the mound areas on both margins of the southern Rockall Trough have fairly active sediment dynamics, as do the mound areas of the Florida–Hatteras slope (Paull et al., 2000) and the slope north of Little Bahama Bank (Mullins et al., 1981). On the eastern margin large sheets of well-sorted sand between the mounds have bedforms suggesting the presence of a fast-flowing, northeast-directed bottom current. The medium-sized sand waves indicate that peak current speeds can reach 40–50 cm/s (Belderson et al., 1982). According to the sonograph interpretations the sand is being actively transported at depths between 600 and 800 m. A poleward current has been recognised on the upper slope west of Scotland and Norway from oceanographic measurements (summarised in Hansen and Østerhus, 2000), from numerical modelling (New and Smythe-Wright, 2001) and from observations of asymmetrical sedimentary bedforms (Kenyon, 1986). The western margin of the Rockall Trough also showed abundant traces of active sand transport, although the overall pattern is more complicated. There is evidence that the overall transport path is along the western margin to the southwest. Mobile sand bedforms here are found at depths from about 500 m to about 1000 m. Some of the sand moves through flat-floored gullies which have probably been conduits for sand throughout much of the mound building period.

The nature of the currents responsible for such sand transport is not very clear from the existing

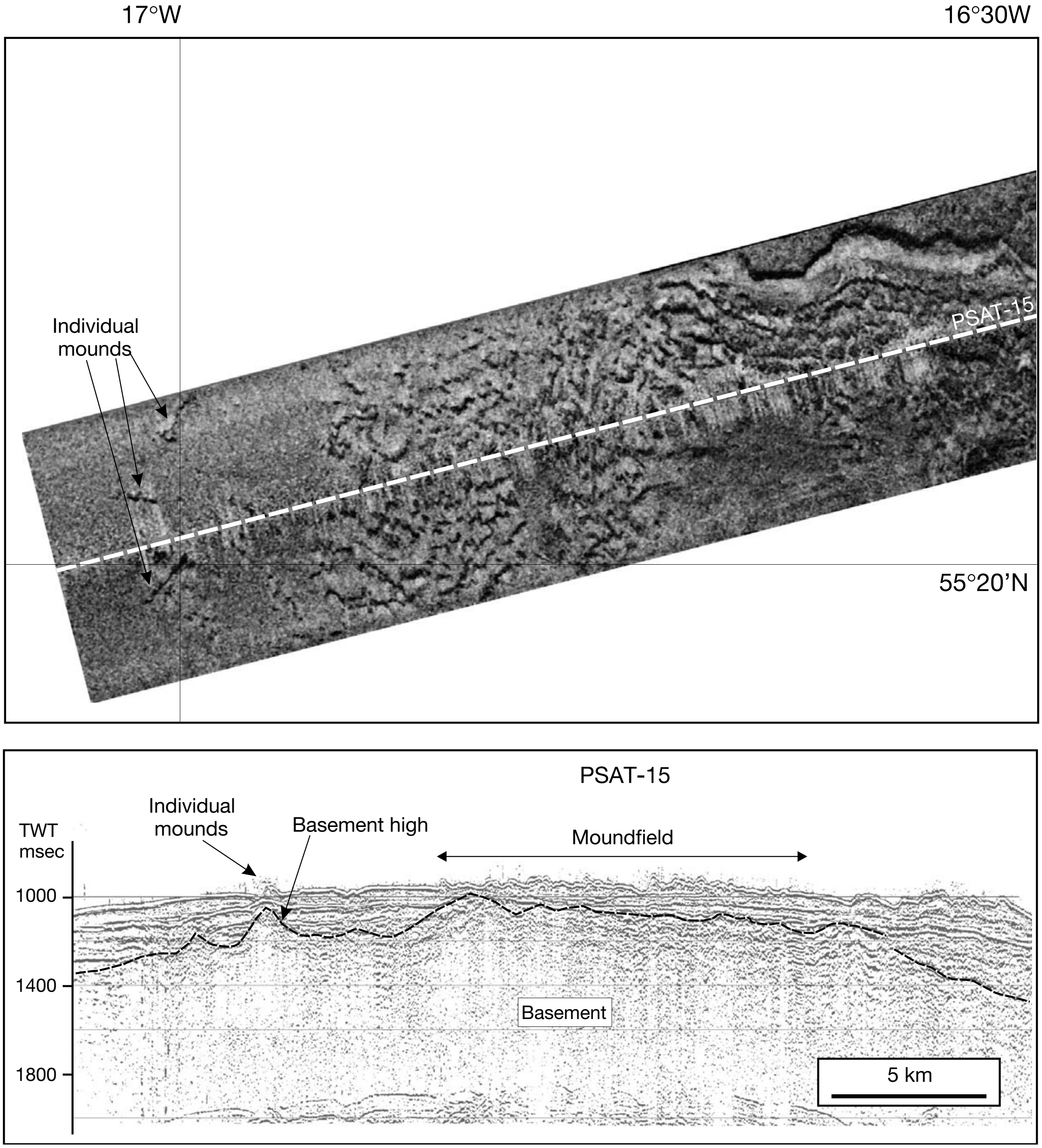


Fig. 14. OKEAN and single-channel seismic record (PSAT-15), located on Fig. 10, showing both individual mounds and the mound field in the southwest part of the survey area. Note that some individual mounds may have built on a protruding basement high.

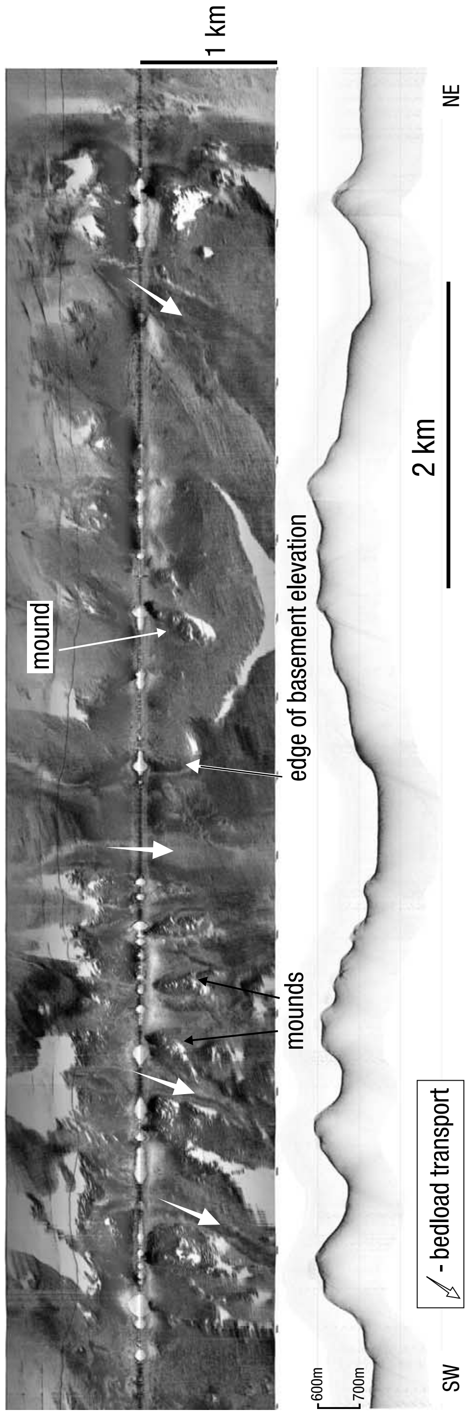


Fig. 15. 30-kHz sonograph and 5-kHz subbottom profiler data, located on Fig. 10, showing mounded features that were proved by sampling to be carbonate mud mounds. The edge of the basement elevation seen on Fig. 13 casts a shadow (white) on the sonograph. There are regular NE–SW oriented mud waves on the mounds.

physical oceanographic data, but it is believed to be due only partly to along-slope currents. The mud waves with crest lines facing downslope, which decorate the Logachev Mounds on Rockall Bank, indicate a long-term current flowing up- and/or downslope. A similar direction of current was deduced from bottom photographs, taken at a location not far downslope in this same area (Lonsdale and Hollister, 1979). Sand ripples at depths between 1315 and 1345 m were attributed to oscillatory internal tidal currents. Internal tide generation is expected around most of the Rockall Trough (Huthnance, 1986; New and Smythe-Wright, 2001) and such across-slope currents have been measured on the upper slope to the west of Scotland (Sherwin and Taylor, 1990). The other type of water movement that could mould slope deposits of mud into waves is cascading currents. These also have been observed on the slope west of Scotland (Hill et al., 1998).

Frederiksen et al. (1992) suggested a close relationship between cold-water coral distribution and zones of internal tidal mixing as the latter would cause an increase in vertical flux of particles to the bottom mixed layer, thus providing enhanced food availability. Buried mounds observed on three-dimensional (3D) seismic data collected in the northern Porcupine Seabight have also been linked with a reversing tidal current, albeit one operating in the past (Huvenne and Henriet, 2001).

The sidescan sonar data and samples show that there are significant amounts of glacigenic coarse material on the upper part of the slope. As shown by studies of the cold-water coral reefs on the Norwegian margin (Freiwald et al., 1997; Holtedahl et al., 1974; Bugge, 1980), such material is extremely suitable for the establishment of coral colonies. The abundant boulders, stone and gravel fragments provide the hard substrate required for settlement (Wilson, 1979). Outcrops of basement rocks, rising above the seafloor, have provided an ideal location for some of the larger mounds.

The presence of pinnacles and scarps, as found in the area of mounds on Rockall Bank, is known to cause local flow acceleration (Huppert and Bryan, 1976) thus providing favourable conditions for suspension feeders, and corals in partic-

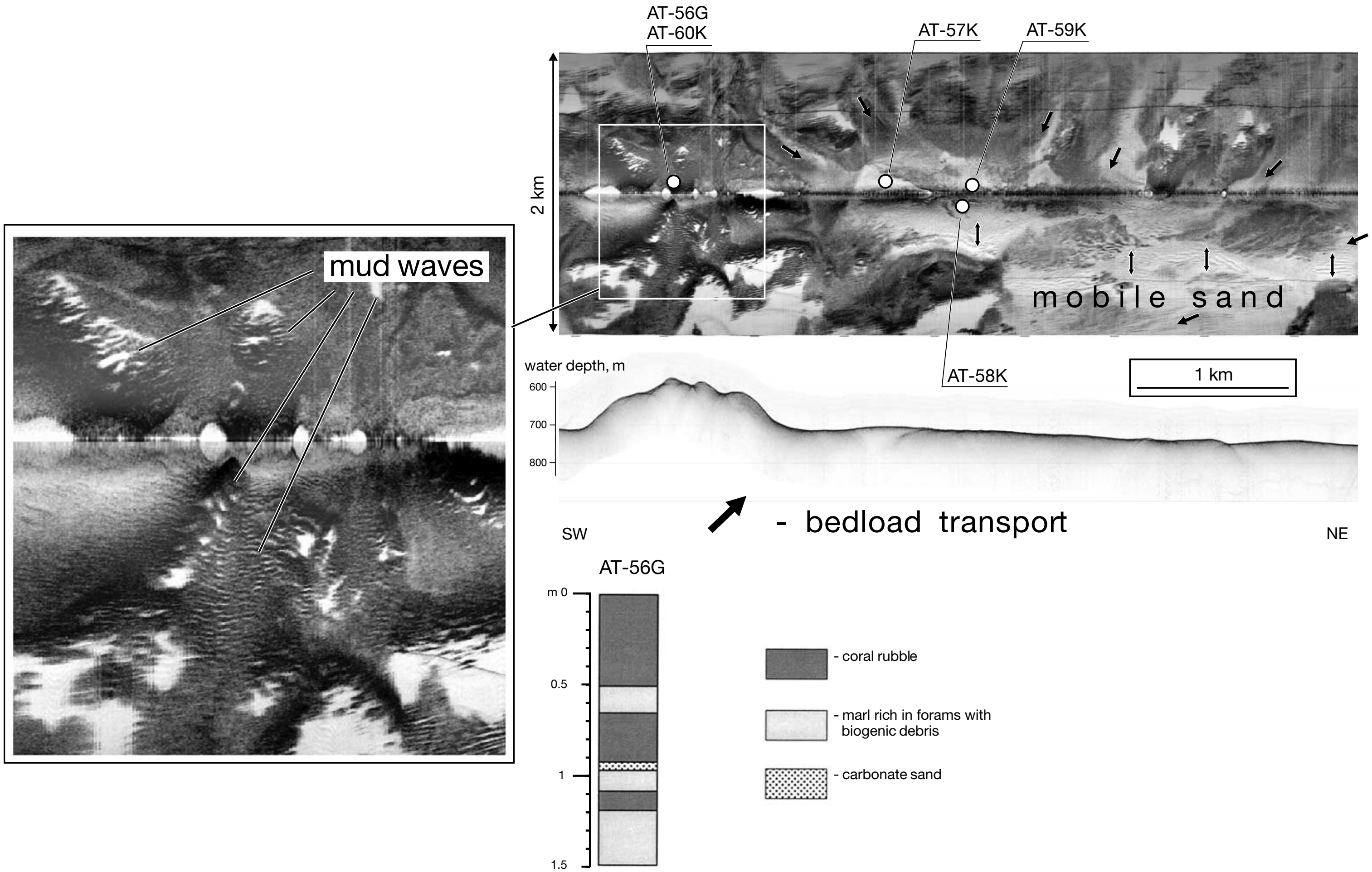


Fig. 16. 30-kHz sonograph showing mud waves decorating slopes of carbonate mounds. The across-slope orientation of the waves points to an upslope- and/or downslope-directed current. Cores from the mounds recovered a sequence of coral rubble layers whereas cores taken from intermound areas showed a dominance of shelly sand.

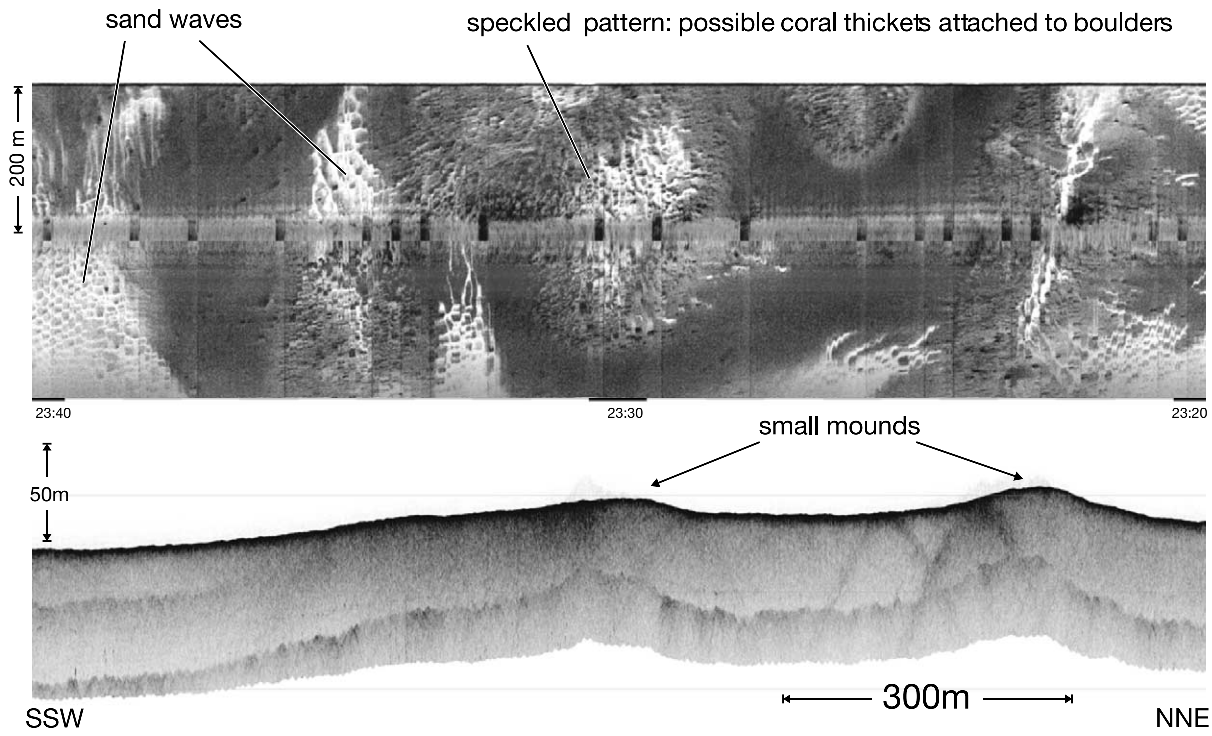


Fig. 17. 100-kHz sonograph of a speckled pattern on a small mound. The speckles are believed to be coral thickets attached to boulders.

ular, to grow (Genin et al., 1986). A good example of a possible carbonate mound, located where flow acceleration would be favoured, is seen on the edge of an escarpment (Fig. 19). This is a similar location to the mounds of the Florida–Hatteras slope (Paull et al., 2000).

The depth distribution of *Lophelia pertusa* generally coincides with the oxygen minimum zone (OMZ) in the North Atlantic (Freiwald, 1998). The presence of the OMZ is established from observations made on the northwestern Porcupine margin (Ellett and Martin, 1973; Arhan et al., 1994), where its formation is attributed to Gibraltar Water. A more specific correlation is made using the data from two oceanographic stations (McCartney, 1992; Dickson and McCave, 1986), located relatively close to the carbonate mounds area, and from the underwater video transect (TVAT-4) across one of the biggest mounds (Fig. 20). This shows that the OMZ lies just below the mound distribution depth and also under a well-expressed nepheloid layer. Well-developed intermediate nepheloid layers have been seen on both margins of the Rockall Trough, in a depth zone between 450 and 700 m (Dickson and McCave, 1986), and on both margins this depth interval fits with the depth range of mound occurrence. An intermediate nepheloid layer has also been encountered in the Porcupine Seabight (Rice et al., 1991) and correlated with the depth range of seabed carbonate mounds (De Mol et al., 1998), although it is in fact a bit deeper than the mounds. These nepheloid layers are important as a source of detrital organic particles, increasing the food availability for bottom fauna (Frederiksen et al., 1992), and their presence may be crucial for the formation of mature *Lophelia* reefs.

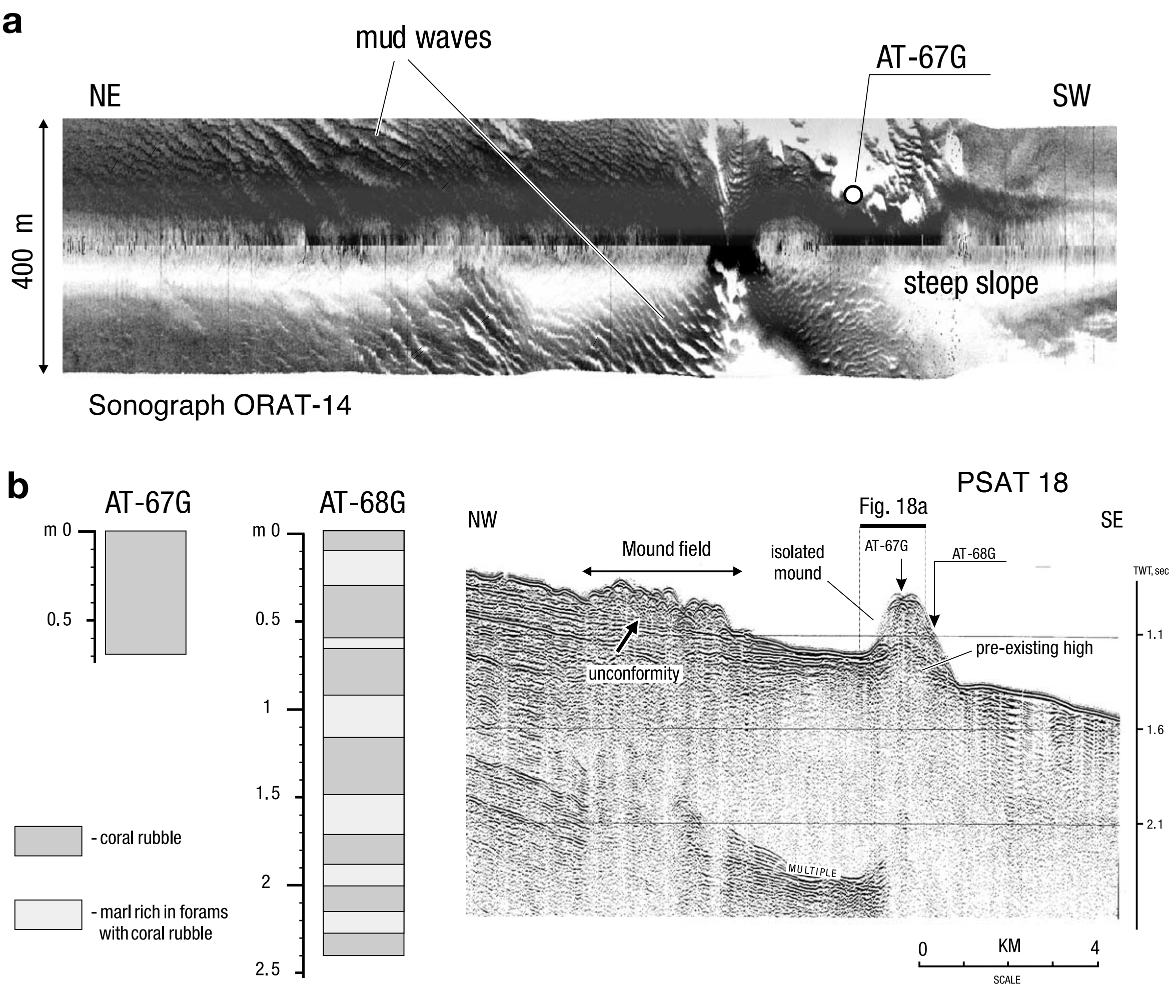


Fig. 18. 100-kHz sonograph (a) and single-channel airgun profile (b) across a large isolated carbonate mud mound building on a pre-existing basement high. Note mud waves decorating the slopes of the mound. Cores collected from the mound recovered a sequence of coral rubble and grey marl.

4.3. Evolution of a mound province and factors controlling it

A simple model of possible mound province evolution and development is offered (Fig. 21). It is based on seismic sections, showing details of mound relationships with the sedimentary succession, and on sidescan sonar maps of mound morphology, distribution pattern and associated sedimentary processes. Seismic lines show a well-marked unconformity preceding the growth of mounds in all of the known mound provinces in this part of the northeast Atlantic. It is interpreted as marking a major change of sedimentary environment, possibly due to the onset of a bottom current-dominated depositional regime. The sedimentary section above the unconformity usually has a seismic signature that indicates the presence of drifts built by currents (Figs. 3 and 13). Strong bottom currents have also caused extensive winnowed deposits. These are particularly coarse because of the significant volumes of ice-rafted material introduced to the margin during and at the end of glacial periods. The winnowed boulder and gravel floors offer an opportunity for extensive cold-water coral colonisation of the

Table 1
Results of bottom sampling on the southwestern Rockall Trough margin

Core no.	Gear	Latitude	Longitude	Water depth (m)	Recovery[a] (cm)	Sedimentary summary
AT-55G	Gravity corer	55°32.22′N	15°46.82′W	825	CC	Small amount of poorly sorted sand, lithic fragments, shell fragments, and some corals
AT-56G	Gravity corer	55°34.64′N	15°38.67′W	598	143	Alternation of layers of foraminiferal ooze rich in corals and without corals. Sandy layer with dropstones
AT-57G	Gravity corer	55°34.95′N	15°37.67′W	714	CC	2 cm^3 of poorly sorted medium-grained sand, shell fragments, and some small clasts
AT-58G	Gravity corer	55°35.00′N	15°37.23′W	698	CC	10 cm^3 of poorly sorted medium-grained sand rich in shell fragments, coral fragments, and few small clasts
AT-59K	Kasten corer	55°35.10′N	15°37.23′W	700	CC	Same material as AT-58G recovered
AT-60K	Kasten corer	55°34.65′N	15°38.67′W	590	50	Large amount of corals, some alive, and foraminiferal ooze
AT-61K	Kasten corer	55°36.75′N	15°31.88′W	594	20	Broken corals, foraminiferal ooze, and shell fragments
AT-62G	Gravity corer	55°36.79′N	15°31.91′W	604	61	Living corals at the top, foraminiferal ooze, and coral debris
AT-63G	Gravity corer	55°36.61′N	15°32.25′W	657	174	Alternation of foraminiferal ooze rich in coral debris and layers with smaller amount of corals
AT-64G	Gravity corer	55°33.34′N	15°23.70′W	1135	CC	Very small quantity of fine-grained sand with some small clasts
AT-65G	Gravity corer	55°31.39′N	15°29.43′W	1140	CC	Small amount of medium-grained sand with pebbles, shell fragments and live sponges
AT-66G	Gravity corer	55°31.17′N	15°30.20′W	1210	CC	0.5 cm^3 of poorly sorted sand
AT-67G	Gravity corer	55°28.78′N	15°50.07′W	684	61	Corals dead and alive, foraminiferal ooze
AT-68G	Gravity corer	55°28.34′N	15°49.73′W	870	241	Corals and foraminiferal ooze mixture; some layers with less amount of coral debris

[a] CC = recovery in core catcher only.

upper slope. It is surmised that the areas of coral build-ups result in the formation of carbonate mud mounds due to the breakdown of the corals and by the trapping of sediments, transported as both suspended and bed load. Fields of closely spaced mounds are found not only on the present day southwestern Rockall Trough margin but also in the Magellan mound province of the northern Porcupine Seabight, where they are seen on a 3D seismic survey as buried mounds (Huvenne and Henriet, 2001). A further field of closely spaced buried mounds is reported from the eastern Porcupine Seabight (Henriet et al., in press). Such a closely spaced mound field has not developed on the northern Porcupine Bank, perhaps because it was prevented by the high current speed, which would limit the availability of food and also hinder initial coral settlement (Frederiksen et al., 1992). Instead, large individual mounds have formed above pre-existing rocky outcrops, which allow the corals to grow clear of burial by mobile bedload. In the Magellan mound province of the Porcupine Seabight the rate of hemipelagic sedimentation has apparently prevailed over the rate of mound growth and as a result most of the mounds are buried under a cover of Quaternary drifts, with only a few large mounds still expressed in the seafloor topography. The preservation of the Logachev Mound field on the Rockall Bank is believed to be related to a relatively low sedimentation rate. This margin represents a special location where coral communities benefited from favourable environmental conditions and the growth of carbonate build-ups was not suppressed by a high supply of terrigeneous material. Fields of near-contiguous

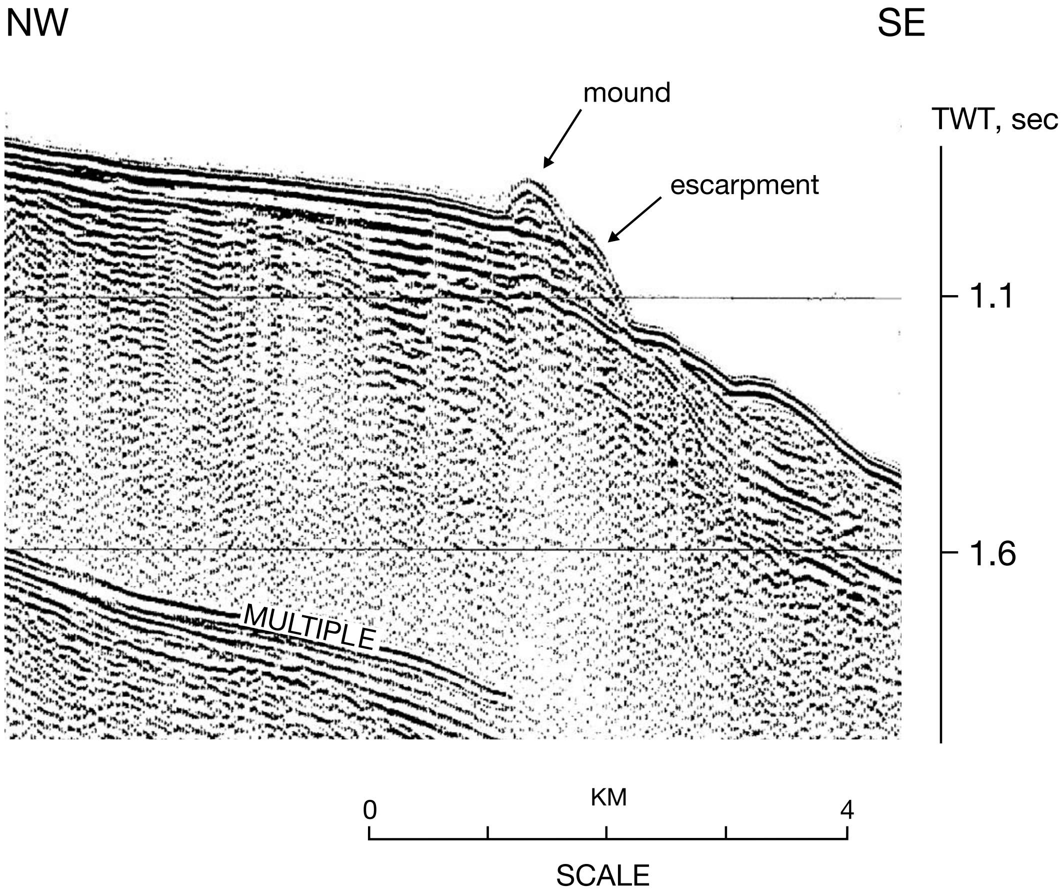


Fig. 19. Fragment of seismic line PSAT-20 showing a probable, but unsampled, carbonate mound on the top edge of an escarpment (for location see Fig. 10).

mounds may thus be a stage in development beyond those proposed by Squires (1964) and Mullins et al. (1981), who recognised an isolated coral colony stage, a coral thicket stage, a coral coppice stage and a bank or mound stage.

5. Conclusions

These first detailed observations of the carbonate mounds on the margins of the southern Rockall Trough indicate that their development is controlled by a number of factors co-existing in a narrow zone of the upper slope. Active hydrodynamic seabed conditions and availability of glacigenic coarse material provide the hard ground necessary for the establishment of a coral colony. Association of the *Lophelia* mound distribution depth with occurrence of intermediate nepheloid layers, coinciding with the slope current and with internal tidal currents, suggests that the nepheloid layers are important for long-term food supply sustaining persistent growth of mature cold-water coral mounds. The balance between bottom current speed, mound growth rate and sedimentation rate plays an important role in the formation of large mound fields. Fast-flowing bottom currents can set restrictions on food availability and larvae settlement while high sedimentation rate, due for instance to bottom current-enhanced deposition, can lead to the almost complete burial of a mound field.

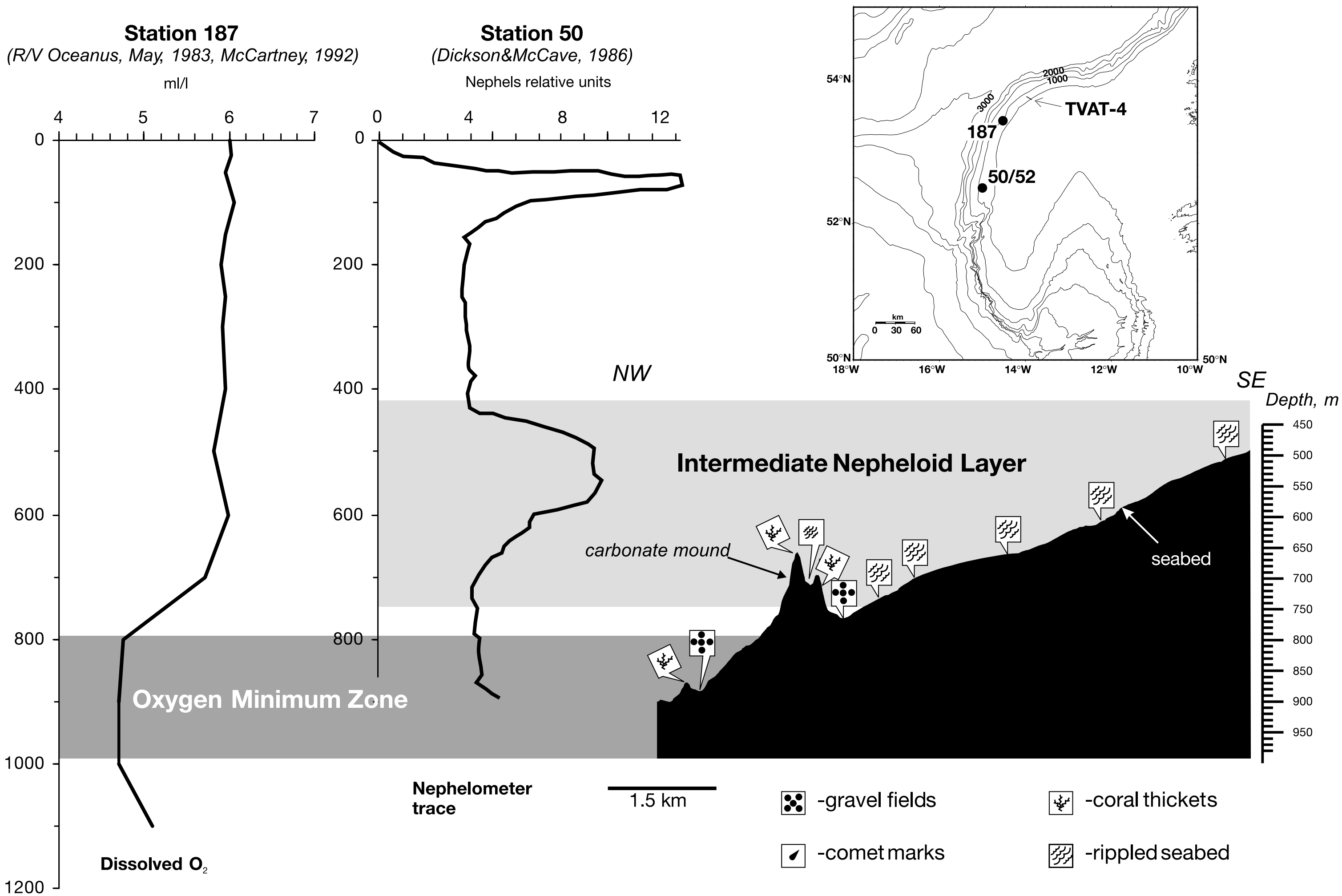


Fig. 20. Depth of occurrence of carbonate mounds on the northern Porcupine Bank and vertical profiles of dissolved oxygen and nephels. The bottom profile and character of the seabed are analysed from the underwater video transect (TVAT-4).

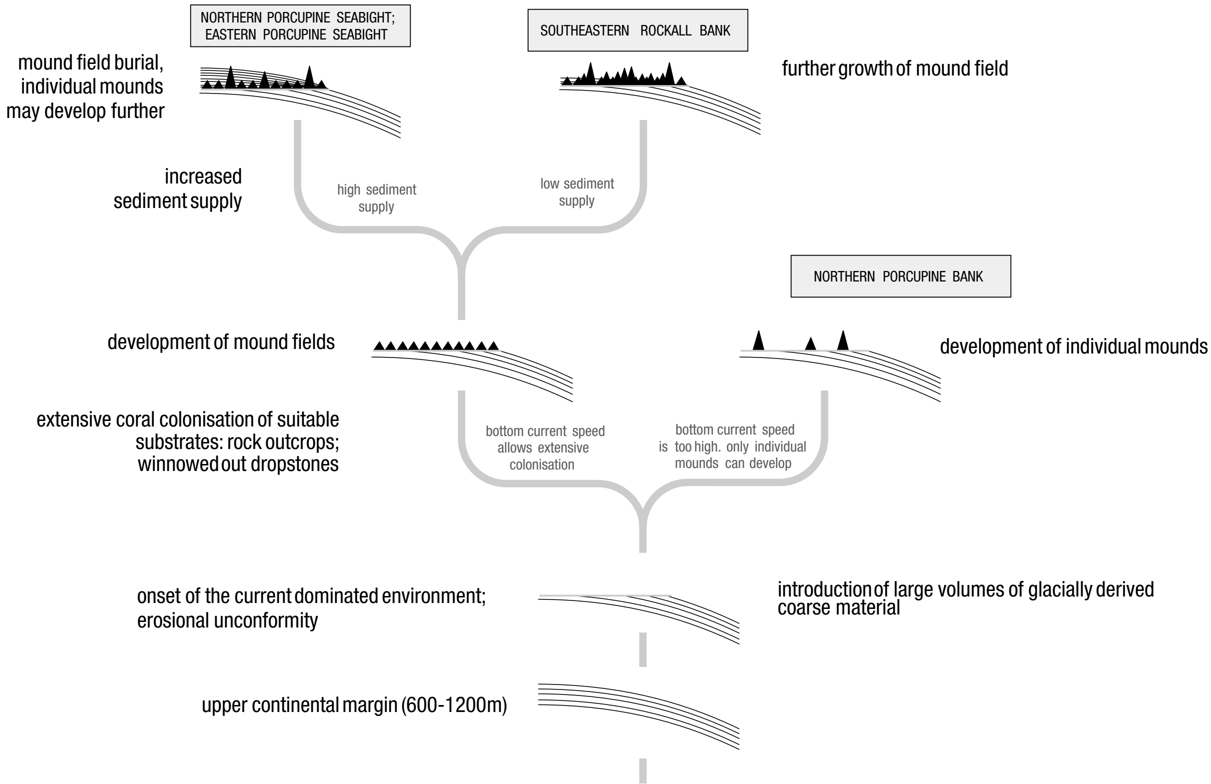


Fig. 21. Generalised model of mound province development under different evolutionary scenarios.

No link between mound occurrence and the seepage of methane or other gases, as suggested by Hovland et al. (1994) and Henriet et al. (1998), has been corroborated by any of these observations.

Acknowledgements

Financial support for the 7th Training-Through-Research cruise came from various sources among which were the EU MAST III projects CORSAIRES and ENAM II, the Intergovernmental Oceanographic Commission (IOC) of UNESCO, and the Ministries of Science and Technology and of Natural Resources of the Russian Federation. Additional support was provided by national funding institutions and universities in Belgium, Denmark, Ireland and the UK. Thanks are due to Captain A. Arutyunov and the skilled crew of the R/V *Professor Logachev* for the successful execution of the cruise. Mounds in the Rockall Trough were, kindly, brought to our attention by Professor David Roberts (BP Amoco) and Dr Alex Jones (Phillips Petroleum UK). Water column property data used for this study were obtained from the Global Ocean Observation Database (GOODBase, http://oceans.ucsd.edu/goodbase/), which incorporates data from the World Ocean Database 1998 CD ROM set, published by the Ocean Climate Laboratory of the National Oceanographic Data Center (NOAA/NESDIS/NODC). We also wish to express our thanks to and gratefully acknowledge the constructive comments of Peter Croker and Terry Scoffin.

References

Arhan, M.A., de Verdière, C., Mémery, L., 1994. The eastern boundary of the subtropical North Atlantic. J. Phys. Oceanogr. 24, 1295–1316.

Belderson, R.H., Johnson, M.A., Kenyon, N.H., 1982. Bedforms. In: Stride, A.H. (Ed.), Offshore Tidal Sands, Processes and Deposits. Chapman and Hall, London, pp. 27–57.

Belderson, R.H., Kenyon, N.H., Wilson, J.B., 1973. Iceberg plough marks in the northeast Atlantic. Palaeogeogr. Palaeoclimatol. Palaeoecol. 13, 215–224.

Bugge, T., 1980. Øvre lags geologi på kontinentalsokkelen utenfor Møre og Trøndelag. Institutt for Kontinentalsokkelundersøkelser, Report, 104, pp. 1–44.

De Haas, H., Grehan, A., White, M. and shipboard scientists, 2000. Cold water corals in the Porcupine Bight and along the Porcupine and Rockall Bank margins. Cruise report R.V. Pelagia, cruise M2000 (64PE165).

De Mol, B., Keppens, E., Swennen, R., Henriet, J.P., 1998. Isotopic characterisation of ahermatypic coral on a 'Hovland' mound. In: De Mol, B. (Ed.), Geosphere–Biosphere Coupling: Carbonate Mud Mounds and Cold Water Reefs. International Conference and 6th Post-Cruise Meeting of the Training Through Research Programme. Gent, Belgium, 7–11 February 1998. Intergovernmental Oceanographic Commission Workshop Reports 143, UNESCO, pp. 31–32.

Dickson, R.R., McCave, I.N., 1986. Nepheloid layers on the continental slope west of Porcupine Bank. Deep-Sea Res. 33, 791–818.

Ellett, D.J., Martin, J.H., 1973. The physical and chemical oceanography of the Rockall Channel. Deep-Sea Res. 20, 585–625.

Frederiksen, R., Jensen, A., Westerberg, H., 1992. The distribution of the scleractinian coral *Lophelia pertusa* around the Faeroe Islands and the relation to internal tidal mixing. Sarsia 77, 157–171.

Freiwald, A., 1998. Geobiology of Lophelia Pertusa (Scleractinia) reefs in the North Atlantic. Unpublished Thesis, University of Bremen, Bremen.

Freiwald, A., Henrich., R., Pätzold, J., 1997. Anatomy of a deep-water coral reef mound from Stjernsund, West-Finnmark, northern Norway. In: James, N.P., Clarke, J.A.D. (Eds.), Cool-Water Carbonates. SEPM Special Publication 56, pp. 141–161.

Genin, A., Dayton, P.K., Lonsdale, P.F., Spiess, F.N., 1986. Corals on seamount peaks provide evidence of current acceleration over deep-sea topography. Nature 322, 59–61.

Hansen, B., Østerhus, S., 2000. North Atlantic–Nordic seas exchanges. Prog. Oceanogr. 45, 109–208.

Henriet, J.P., De Mol, B., Pillen, S., Vanneste, M., Van Rooij, D., Versteeg, W., Croker, P.F., Shannon, P.M., Unnithan, V., Bouriak, S., Chachkine, P., 1998. Gas hydrate crystals may help build reefs. Nature 391, 647–649.

Henriet, J.P., Van Rooij, D., Huvenne, V., De Mol, B., Guidard, S., in press. Mounds and sediment drift in the Porcupine Basin, west of Ireland. In: European Margin Sediment Dynamics: Sidescan Sonar and Seismic Images. Springer, Berlin.

Hill, A.E., Souza, A.J., Jones, K., Simpson, J.H., Shapiro, G.I., McCandliss, R., Wilson, H., Leftley, J., 1998. The Malin cascade in winter 1996. J. Mar. Res. 56, 87–106.

Holtedahl, H., Haldorsen, S., Vigran, J.O., 1974. Two sediment cores from the Norwegian continental shelf between Haltenbanken and Frøyabanken (64°06′N, 7°39′E). Nor. Geol. Unders. 304, 1–20.

Hovland, M., Croker, P.F., Martin, M., 1994. Fault-associated seabed mounds (carbonate knolls?) off western Ireland and North-west Australia. Mar. Petrol. Geol. 11, 232–246.

Huppert, H.E., Bryan, K., 1976. Topographically generated eddies. Deep-sea Res. 23, 655–679.

Huthnance, J.M., 1986. The Rockall slope current and shelf-edge processes. Proc. R. Soc. Edinb. 88B, 83–101.

Huvenne, V., Henriet, J.P., 2001. 3D spatial and morphological analysis of a buried mound province. Abstracts of European Union of Geosciences XI Meeting, 749.

Kenyon, N.H., 1986. Evidence from bedforms for a strong poleward current along the upper continental slope of northwest Europe. Mar. Geol. 72, 187–198.

Kenyon, N.H., Ivanov, M.K., Akhmetzhanov, A.M. (Eds.), 1998. Cold water carbonate mounds and sediment transport on the Northeast Atlantic margin. Preliminary results of geological and geophysical investigations during the TTR-7 cruise of R/V Professor Logachev in co-operation with the CORSAIRES and ENAM 2 programmes. Intergovernmental Oceanographic Commission Reports, Technical series, 52, UNESCO, 178 pp.

Lonsdale, P., Hollister, C.D., 1979. A near-bottom traverse of Rockall Trough: hydrographic and geological inferences. Oceanol. Acta 2, 91–105.

McCartney, M.S., 1992. Recirculating components to the deep boundary current of the northern North Atlantic. Prog. Oceanogr. 29, 283–383.

Mullins, H.T., Newton, C.R., Heath, K., Vanburen, H.M., 1981. Modern deep-water coral mounds north of Little Bahama Bank: criteria for recognition of deep-water coral bioherms in the rock record. J. Sediment. Petrol. 51, 999–1013.

New, A.L., Smythe-Wright, D., 2001. Aspects of the circulation in the Rockall Trough. Cont. Shelf Res. 21, 777–810.

Paull, C.K., Neumann, A.C., am Ende, B.A., Ussler, W., III, Rodriguez, N.M., 2000. Lithoherms on the Florida–Hatteras slope. Mar. Geol. 166, 83–101.

Rice, A.L., Billett, D.S.M., Lampitt, R.S., Thurston, M.H., 1991. The Institute of Oceanographic Sciences biology programme in the Porcupine Seabight: background and general introduction. J. Mar. Biol. Assoc. UK 71, 281–310.

Saoutkine, A., 1998. Influence of surface-water temperature oscillations on the development of deep-water coral buildups in the Porcupine basin (North Atlantic). In: De Mol, B. (Ed.), Geosphere–Biosphere Coupling: Carbonate Mud Mounds and Cold Water Reefs. International Conference and 6th Post-Cruise Meeting of the Training Through Research Programme. Gent, Belgium, 7–11 February 1998. Intergovernmental Oceanographic Commission Workshop Reports 143, UNESCO, pp. 25–26.

Scoffin, T.P., Alexandersson, E.T., Bowes, G.E., Clokie, J.J., Farrow, G.E., Milliman, J.D., 1980. Recent, temperate, subphotic carbonate sedimentation; Rockall Bank, Northeast Atlantic. J. Sediment. Petrol. 50, 331–355.

Sherwin, T.J., Taylor, N.K., 1990. Numerical investigations of linear internal tide generation in the Rockall Trough. Deep-Sea Res. 10, 1595–1618.

Squires, D.F., 1964. Fossil coral thickets in Wairarapa, New Zealand. J. Palaeontol. 38, 904–915.

van Weering, Tj.C.E, de Haas, H., Akhmetzhanov, A.M., Kenyon, N.H., in press. Giant carbonate mounds along the Porcupine and SW Rockall Trough Margins. In: European Margin Sediment Dynamics: Sidescan Sonar and Seismic Images. Springer, Berlin.

Wilson, J.B., 1979. 'Patch' development of the deep-water coral *Lophelia pertusa* (L.) on Rockall Bank. J. Mar. Biol. Assoc. UK 59, 165–177.